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Bioclimate and health in urban and rural areas of Bangladesh – short- and long-term effects of atmospheric thermal conditions on human mortality

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"Whoever wishes to investigate medicine properly, should proceed thus: in the first place to consider the seasons of the year, and what effects each of them produces for they are not at all alike, but differ much from themselves in regard to their changes. Then the winds, the hot and the cold, especially such as are common to all countries, and then such as are peculiar to each locality...."

— Hippocrates in "On Airs, Waters, and Places" [1], ~ 400BC

[1] Hippocrates (2004, reprint): On Airs, Waters, and Places. Kessinger Publishing's Rare Reprints.

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ABSTRACT

Climate and weather have profound effects on human health. With the projected consequences of climate change, research on the health-atmosphere relationship has increasingly been brought into the focus of scientific attention. To date, several studies have established a relationship between atmospheric short- or long -term conditions and human mortality. Nevertheless, the majority of scientific evidence refers to industrialised countries located in the mid-latitudes. The insights gained from these studies permit few conclusions to be drawn about the atmosphere-health relationship in tropical developing countries. The primary objective of this thesis was to advance our understanding of atmospheric effects on mortality in Bangladesh, a tropical country with low socio-economic status and strong urbanisation processes. Furthermore, effect modifications arising from non-atmospheric conditions were investigated with special consideration of urban versus rural environments. As a first step, a systematic literature review was conducted in order to compile and systematically analyse all relevant research on the subject matter. Next, three-hourly meteorological data was used to model thermo-physiological conditions in Bangladesh and derive tempo-spatial differences in health-relevant bioclimatological settings. Finally, an extensive analysis of atmospheric short- and long-term effects on mortality was conducted using various generalised linear and additive models (GLMs/GAMs). Generally, this study revealed a strong association between atmospheric conditions and mortality. Mid- to long-term seasonal effects were demonstrated as well as more immediate short- to mid-term thermal effects. Despite the tropical climate associated with constantly high temperatures, a strong dominance of winter and cold-related excess mortality was observed. Nevertheless, a secondary summer maximum and an increase in mortality with elevated temperatures were observed for several locations, causes of death and age groups. In particular, all-cause and cardiovascular mortality in urban areas was found to be subject to intense and long-lasting heat effects. Likewise, the elderly population above 65 years was subject to heat-related mortality. Given the strong urbanisation trends, the ageing of populations and the increase in cardiovascular diseases, adverse heat effects are likely to become more prevalent in Bangladesh and other developing countries. Furthermore, rising temperatures due to global warming may indeed serve to aggravate such heat effects.

ZUSAMMENFASSUNG

Klima und Wetter üben einen entscheidenden Einfluss auf die menschliche Gesundheit aus. Die prognostizierten Folgen des Klimawandels haben die Forschung über die Zusammenhänge zwischen Atmosphäre und Gesundheit in den Mittelpunkt des wissenschaftlichen Interesses gerückt. Bis zum jetzigen Zeitpunkt konnten verschiedene Studien einen Zusammenhang zwischen atmosphärischen Lang- und Kurzzeit-Zuständen und Mortalität aufzeigen. Jedoch bezieht sich der Großteil dieser Forschung auf die Industrieländer der Mittelbreiten und Erkenntnisse aus solchen Arbeiten erlauben nur wenige Schlussfolgerungen über die Beziehung zwischen Atmosphäre und Gesundheit in tropischen Entwicklungsländern. Das vorrangige Ziel dieser Arbeit war es, das Verständnis über atmosphärische Einflüsse auf Sterblichkeit in Bangladesch, einem tropischen Land mit niedrigen sozioökonomischen Standards und starken Urbanisierungsprozessen, zu erweitern. Darüber hinaus wurden Modifikationen erfasst, welche durch nicht-atmosphärische Einflüsse hervorgerufen werden. Besondere Berücksichtigung fanden insbesondere Unterschiede zwischen ländlichen und städtischen Gebieten. Ein erster Schritt bestand in einer systematischen Literaturrecherche, welche das Ziel verfolgte, jegliche relevante Forschung zu diesem Themenbereich zusammen zu tragen und systematisch zu analysieren. Im Anschluss wurden meteorologische dreistündige Werte genutzt, um thermophysiologische Bedingungen in Bangladesch zu modellieren und zeitliche und räumliche Ausprägungen gesundheitsrelevanter bioklimatischer Zustände herzuleiten. Den Abschluss bilden umfangreiche Analysen zu atmosphärischen Einflüssen auf die Mortalität mittels verschiedener Generalisierter Linearer und Additiver Modelle (GLM/GAM). Im Allgemeinen zeigt die Studie einen starken Zusammenhang zwischen atmosphärischen Zuständen und Mortalität auf. Mittel- bis langfristige saisonale Effekte ebenso wie unmittelbarere kurz- bis mittelfristige thermische Effekte wurden verdeutlicht. Trotz des tropischen, durch andauernd hohe Temperaturen geprägten Klimas, wurde eine ausgeprägte Übersterblichkeit im Winter und im Zusammenhang mit niedrigen Temperaturen beobachtet. Abhängig von Gebiet, Todesursache und Alter wurden in einigen Fällen ein sekundäres Sommermaximum und ein Anstieg der Mortalität bei erhöhten Temperaturen gefunden. Insbesondere Gesamt- und kardiovaskuläre Mortaliät in Städten zeigte einen starken und lang andauernden Anstieg in Folge von Hitze. Ebenso waren Bevölkerungsgruppen über 65 Jahren stark von hitzebedingter Mortalität betroffen. Aufgrund der intensiven Urbanisierungstendenzen, der Alterung der Gesellschaft und der Zunahme kardiovaskulärer Erkrankungen ist es wahrscheinlich, dass solche schädlichen Hitzeeffekte in der Zukunft in Bangladesch und anderen Entwicklungsländern zunehmen werden. Ansteigende Temperaturen, verursacht durch den Klimawandel, können die Situation weiterhin verschärfen.

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CHAPTER 1: INTRODUCTION

1.1 ATMOSPHERE AND HEALTH

Climate and weather have a profound effect on human health and well-being. Every individual has probably experienced the beneficial or disadvantageous effects of certain weather conditions on a personal level. While for most, this atmospheric effect[2] does not result in a critical state of health, more susceptible and vulnerable individuals run the risk of suffering from severe health-related consequences. A multitude of studies have established a relationship between short- and long-term atmospheric conditions and morbidity or mortality. The great majority of evidence refers to variations in cardio-respiratory and infectious diseases with varying ambient thermal conditions (to a certain extent hydrological aspects were also considered). So far, our understanding of this matter is based on eco-epidemiological studies[3] conducted in industrialised countries of the mid-latitudes. Indeed, studies assessing mortality outnumber those assessing morbidity. Generally, recent studies showed increased mortality levels at the low and high end of the temperature range (Kunst et al. 1993; Basu and Samet 2002; Curriero et al. 2002; Basu 2009). Moreover, research revealed that the magnitude of temperature effect and the shape of the atmosphere-mortality relationship are determined by non-atmospheric influences such as socio-economic status, human behaviour, or the spatial characteristics of an area. Differences were found between different sub-populations, rural and urban areas and

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[2] By definition, atmospheric effects comprise both physical and chemical effects. However, this thesis focuses on physical effects. Chemical effects (i.e., the impacts of air pollution) were subject only to marginal assessment, as the lack of adequate long-term data did not allow systematic analysis. Later chapters of this thesis account for air pollution effects by incorporating dummy variables into regression models.

[3] Eco-epidemiological studies are based on aggregated data (mostly gathered on the administrative level) and the units of analysis are populations rather than individuals

between cities with diverse characteristics; even intra-urban differences were found (Basu and Samet 2002; Curriero et al. 2002; Medina-Ramón and Schwartz 2007; Basu 2009; Gabriel and Endlicher 2011). Given such complex interactions between atmospheric and non-atmospheric factors, applying the insights gained from studies conducted in a particular region to other regions and populations seems often unfeasible. In particular, studies conducted in moderate climates with predominantly high socio-economic standards allow few conclusions to be drawn about atmospheric effects in a tropical developing country.

Considering the modifying influence of non-atmospheric conditions, the future impact of weather and climate will not only depend on the future climate but also various other prospective scenarios. Changes in socio-economic and socio-cultural conditions have led to far-reaching changes in the burden of disease profile in many developing countries of the world. This epidemiological transition is usually accompanied by an increase in cardio-respiratory and other non-communicable diseases while the traditional infectious diseases continue to prevail (Reddy and Yusuf 1998; Yusuf et al. 2001; Marshall 2004). Projections of mortality from 2002 to 2030 show that non-communicable mortality will continue to increase (Murray and Lopez 1997; Mathers and Loncar 2006). In addition to this projected double burden of disease[4], the demographic pattern in developing countries will change. The number of persons aged 65 years and older is expected to increase drastically within the coming decades (Cohen 2003; Smith and Mensah 2003; United Nations 2004).

The worldwide increase and speedup in urbanisation processes is moreover likely to shape atmospheric impacts on human health. In 2008 the number of people living in urban areas equalled this living in rural areas for the first time in history; a phenomenon often referred to as the “urban turn” (United Nations 2008; Butsch et al. 2009). According to United Nations projections, urban areas will continue to grow

[4] Coexistence of traditional infectious diseases with modern non communicable and cardiovascular diseases

with a growth rate registering 2.1% per year from 2010 to 2025. While the urban population of the more developed regions is projected to increase only modestly (0.6% p.a.), virtually all of the world's population growth will be absorbed by the urban areas of the less and least developed regions (2.1 p.a.% and 3.8% p.a. respectively) (Figure 1.1). Asia, in particular, is projected to see its urban population increase and by mid-century most of the urban population of the world (54%) will be concentrated in Asia (United Nations 2008, 2010).

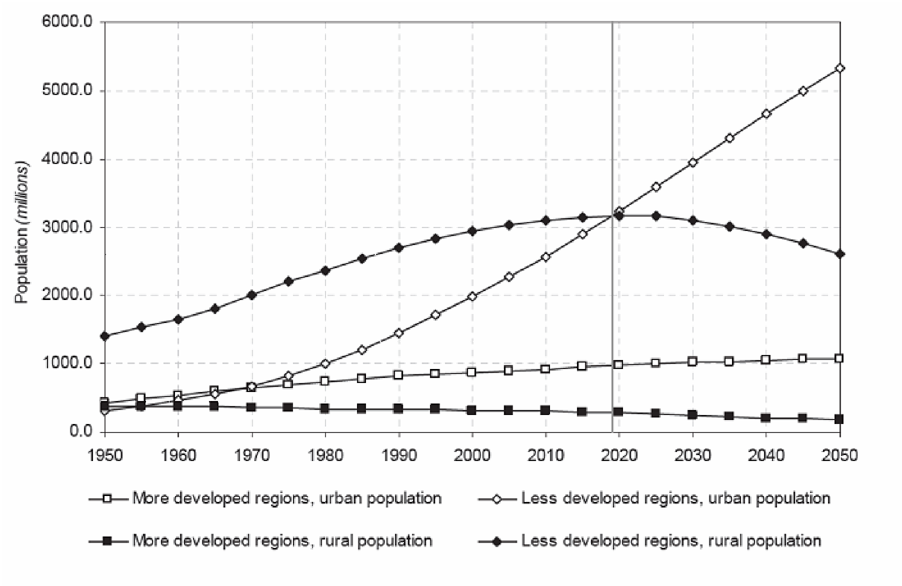

Figure 1.1: Urban and rural population trends by development group. The results are shown for development groups in six major areas (i.e., Africa, Asia, Europe, Latin America and the Caribbean, Northern America and Oceania) and 21 regions (United Nations 2008)

Today's 3.4 billion urban dwellers are distributed unevenly between urban settlements of different size. In discussing urbanisation, the focus often rests on large cities and megacities. In 2007, 19 urban agglomerations qualified as megacities, i.e. cities with more than 10 million inhabitants. The current number of megacities in the world is expected to increase to 27 by 2025. Their strong development dynamics and high concentrations of population, infrastructure, economic power and administrative and political functions lead scholars to consider (mega)cities as nodal points in today's globalised world (Kraas 2003; Kraas 2007). On the other hand, (mega)cities are also confronted by a number of serious challenges, including increasing poverty, socio-spatial fragmentation processes, loss of governability and a strongly expanding informal sector (Kraas 2003). Moreover, they often face ecological challenges such as air, water and soil pollution and a heavy burden of disease.

These worldwide urbanisation trends are also prevalent in Bangladesh. On a nationwide level, urban growth amounts to 3.2%. Dhaka, the capital city, is currently growing at an estimated 4.2% per year, one of the highest rates amongst Asian cities (United Nations 2008, 2010). Today, with approximately 12 Mio inhabitants, Dhaka has advanced to become the 11th biggest megacity in the world; projections forecast its growth into the fourth biggest megacity (forecasted population 22 million) by 2025 behind Tokyo (36 million), Mumbai (26 million), and Delhi (23 million) (United Nations 2008). The largest share of the formerly rural migrant population finds shelter in so called urban slums (often also referred to as informal settlements), environments exhibiting the lowest socio-economic standards in the world (Centre for Urban Studies 2006). The combination of Dhaka's rapid development into a megacity coupled with an inadequate urban management system denotes that the city is facing not only slum development but also tremendous problems in terms of infrastructure, environment, management and governance.

Cities are generally associated with both positive and negative effects for public health. Whilst the quality and availability of healthcare provision and health education in urban areas often far outstrips that of rural areas, they are also associated with much worse physical and social environments (Moore et al. 2003; Vlahov et al. 2004; Galea et al. 2005). Faced with these numerous opportunities and challenges, urbanisation has been suggested as the single most important demographic change facing the world population in the 20th century (McMichael 1999). Considering its health-related implications, urbanisation as a phenomenon is becoming increasingly important.

Evidence from western countries suggests that urban areas are more vulnerable to elevated temperatures and heat (Smoyer et al. 2000; Gabriel and Endlicher 2011). Differences in socio-economic status, lifestyles and pre-existing health conditions between the populations of rural and urban areas might represent possible explanations for this phenomenon. In particular, urban areas of developing countries show a much higher incidence of non-communicable diseases such as cardiovascular conditions or diabetes. A lack of physical activity and unhealthy dietary habits are major contributing factors to this disease patterns (Proctor et al. 1996; Shetty 2002; Kelishadi et al. 2008; Khan et al. 2009). In addition, the anthropogenic modification of the urban mesoclimate, the so-called urban heat island (UHI), is likely to increase thermal stress, which could result in increased levels of severe heat exposure and a higher vulnerability of urban populations.

One dynamic which is superimposed to the processes and drivers described above is climate change. The anthropogenically-induced increase in temperatures – triggered mainly by industrially emitted green house gases – is causing a change in long- and short-term weather patterns worldwide. The regional manifestations of climate change are diverse and differ in their characteristics and intensity. For low latitude regions such as Asia or Africa, future projections of climate are accompanied by high uncertainties. Little reliable long-term meteorological data required for model input and validation is available for these regions. So far, some conclusions about climate trends can be drawn from studies analysing past meteorological time series. Studies conducted in South-East Asia registered an increase in hot days and warm nights and a decrease in cold days and nights between 1961 and 1998 (Manton et al. 2001; Tran et al. 2005; Cruz et al. 2006; Cruz et al. 2007). In Bangladesh, studies observed a trend of about 1 Kelvin temperature increase in May and 0.5 Kelvin in November during the 14-year period from 1985 to1998 (Mirza and Dixit 1997; Khan et al. 2000; Mirza 2002). The modelling outputs summarised and published by the IPCC (Intergovernmental Panel of Climate Change) show a 2 to 8 Kelvin increase in temperature in Asia (Figure 1.2). While the magnitude of temperature increase is similar to that exhibited by other regions, the prevailing high temperatures in these regions could make the consequences of an increase in values particularly adverse.

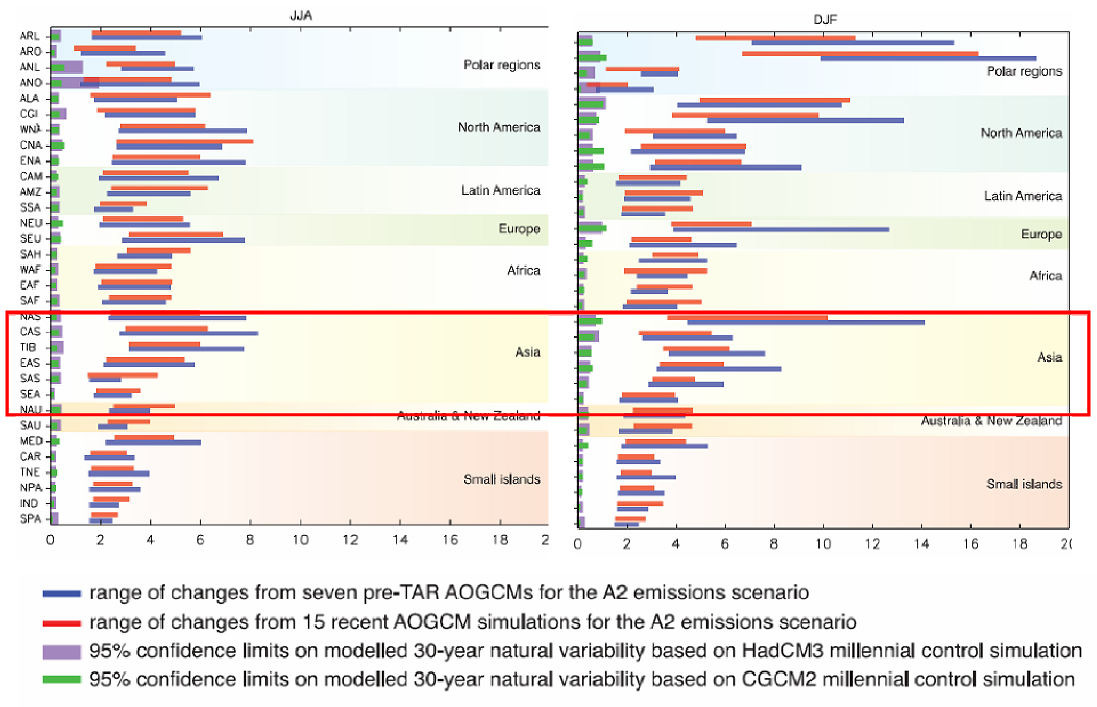

Figure 1.2: Temperature increase (°C/century) for different world regions. Range of winter (DJF: December, January, February) and summer (JJA: June, July, August) temperature up to the end of the 21st century across recent (fifteen models – red bars) and pre-TAR (seven models – blue bars) Atmosphere-Ocean General Circulation Model projections under the Special Report on Emissions Scenarios A2. Results for Asian projections lined by red frame. (Parry et al. 2007:33; slightly modified)

Understanding how climate and weather affect human health is essential for developing adequate programmes of adaptation and response, especially in terms of public health intervention. In particular, the awareness and understanding of the effects of non-atmospheric influences and modifications will determine the efficiency of adaptation and mitigation. The primary objective of this thesis was (1) to investigate short- to long-term atmospheric effects on health in Bangladesh, a tropical developing country. Moreover, (2) modifications of the atmosphere-mortality relationship originating from environmental framework conditions, population characteristic or other non-atmospheric influences were assessed. Special consideration was given to differences in atmospheric impacts in urban versus rural areas. Concluding, (3) findings were discussed against the background of global dynamics and trends, such as climate change, demographic changes, urbanisation and the associated changes in socio-economic and cultural environments.

1.2 APPROACHING THE RESEARCH MATTER AND DEFINING SPECIFIC OBJECTIVES

The lack of work on atmospheric impacts on health in tropical regions, particularly for developing regions is most likely due to limited resources and data availability. Almost all the relevant statistics needed for this kind of research are produced in vital registration systems and developing countries are frequently deficient in this regard. The few studies conducted are often little-noticed due to the dominance of highly sophisticated studies conducted in industrialised countries, often relying on a substantial data basis and published in high ranked journals. To reach an overview of existing research on the topic, all relevant studies on atmosphere-related effects on tropical mortality were compiled and analysed. This task was undertaken in the form of a so-called “systematic review”. Unlike common literature reviews, the systematic review is led by a peer-reviewed protocol in such a way that its outcomes can be reproduced. Within a systematic review a clear research question and concrete inclusion and exclusion criteria for potential studies are defined. After compilation, the studies included are subject to systematic analysis, their findings contrasted and the results elaborated in an integrative manner. The objective of a systematic literature review is to identify and synthesise all the relevant research evidence and prevent the subjective or random selection of articles. The systematic review conducted within the scope of this thesis analysed the effect of weather and season on mortality in tropical climates. The methodological protocol, findings and synthesis of the results is the subject matter of Chapter 2.

Before addressing atmospheric effects on mortality, this thesis assessed the meteorological and (bio)climatological conditions in Bangladesh and Dhaka. Climate and weather are often limited to temperature with some research considering other physical parameters (usually humidity and precipitation). Nevertheless, when considering meteorologically-induced health effects, the totality of all climatological and meteorological parameters affecting the human organism and their interplay are of great relevance. Given the complex nature of the various interactions, so-called thermo-physiological models relating atmospheric conditions to human heat sensation have been developed (Büttner 1938; Parsons 2003). The output parameters of such models are so-called thermo-physiological indices, some kind of equivalent temperatures which reflects the energy gain of the organism under consideration of all relevant meteorological parameters. Chapter 3 models such equivalent temperatures for three stations in Bangladesh and assesses their spatio-temporal characteristics. The research design is threefold, focussing on seasonal fluctuations in bioclimatic conditions, the incidence and stochastic probability of extreme events and the anthropogenic modification of the regional climate. The research of this chapter can be considered as being a climatological approach to health-relevance assessment, relying on the modelling of perceived thermal conditions and statistical analysis.

Before analysing and modelling the mortality data, the atmosphere-health relationship in Bangladesh was conceptualised with special consideration of the megacity of Dhaka. Chapter 4 contains a conceptual framework reflecting the effects of the atmospheric environment on human and public health and showing how these effects are modified on different scales by various external drivers. The process considers local, regional and global aspects and the analysis depicts chains of consequences. Although presenting some findings from air pollution and morbidity data, the strength of this chapter lies in the theoretical consideration of the atmosphere-health relationship in the unique arena of a tropical developing country. Global drivers such as global economic and cultural change or climate change were discussed in consideration of local conditions. Research deficits, needs and possible approaches were elaborated and considered against the background of local and global dynamics.

As a next step, the thesis then investigated human mortality data, linking it to atmospheric conditions. The mortality data used in this study was collected by a sample vital registration system (SVRS) maintained by the Bangladesh Bureau of Statistics. The registration system surveys approximately one million individuals, and vital events such as birth, death, marriage, divorce, migration etc. are continuously recorded. Such data is exceptional for a developing country, allowing an unprecedented level of data analysis and offering a great deal of reliability to the outcomes. Bangladesh was surveyed on a nationwide level, with events being monitored on a daily basis. The SVRS data was used to assess the long-term and short-term effects of atmospheric conditions on mortality. The thesis followed several approaches and considered various effects and strata in an extensive data analysis; the methodology and findings constitute the focus of Chapters 5-7. All three chapters contrast the findings from urban areas with those from rural areas in order to elucidate differences in the health-atmosphere relationship between those two categories.

Chapter 5 assesses seasonal fluctuations in mortality. Seasonal variations in disease and death can be considered as a consequence of seasonally varying factors affecting the etiology of disease. The overriding factors driving these seasonal differences are weather and climate and to a great extent, seasonal variations can be considered as direct mid- to long-term effects of interannual meteorological variations ranging from several weeks to months. Certainly, indirect effects of climate and weather such as seasonal differences in socio-economic status (e.g., harvest vs. planting season), socio-cultural behaviour (e.g., fasting season) or seasonally varying access to infrastructure also need to be considered. The seasonal effect on all-cause mortality as well as cause-specific mortality (e.g., respiratory, cardiovascular, diarrhoeal mortality) was investigated with consideration of the age-specific magnitude of seasonality. In addition to the assessment of mortality fluctuation in urban versus rural areas, the sample was stratified by gender and socio-economic status.

While seasonal variations allow conclusions to be drawn regarding the general influence of varying weather conditions, Chapter 6 assesses the short- to mid-term effects of temperature and thermal conditions ranging from a few days to several weeks. For this purpose generalised liner and additive models (GLMs/GAMs)[5] were used and daily death counts (dependent variable) were modelled as a function of (equivalent) temperature (independent variable), adjusting for several additional influences. The models were fitted separately for urban and rural areas in order to investigate differences in the response to heat. Moreover, temperatures as well as different thermo-physiological indices were used as independent variables and their predictive advantage was evaluated. Using so-called breakpoint models, threshold (equivalent) temperatures constituting temperatures at minimum mortality were determined and the increase in mortality above and below a threshold (equivalent) temperature was predicted.

Chapter 7 comprises an age-specific analysis of short- and long-term meteorological effects on mortality in Bangladesh. In this chapter seasonal as well as thermal effect were investigated. Given the limited number of observations (death counts), cause-specific differences and other strata were left unconsidered in order to allow the distinction between different age groups. The seasonal and thermal effects on children, youths, adults as well as elderly above 65 years were investigated. Considering current and future demographic changes in many developing countries such age-stratified analysis appears particularly relevant. The spectrum of methods accords most widely with the methods used in Chapter 5 and 6. Various types of Poisson regression models (GLMs, GAMs and breakpoint models) were used for assessing atmospheric effects ranging from a few days to several months.

[5] Generalised linear and additive models are particular types of regression model

Chapter 8 summarises the main findings of the thesis and discusses their relevance and implications. The chapter constitutes a synthesis of the preceding chapters and elaborates on the strengths and limitations of the thesis. Finally, directions for potentially relevant future research possibilities are suggested.

1.3 STRUCTURE OF THE THESIS

This thesis is structured in six main sections (Chapters 2-7) as outlined in the research objectives described above. Chapter 8 synthesises the outcomes of the individual chapters, summarising their findings and discussing their implications. Chapters 2-7 are stand alone manuscripts which have been or will be published in journals and books. Chapters 4-6 make up the core of this thesis, thus fulfilling the formal requirement of a cumulative doctoral dissertation. The nature of a cumulative dissertation envisaging publication in a variety of international publications means that a certain amount of repetition in the thesis could not be avoided. Moreover, minor inconsistencies concerning formal critera (e.g., British vs. American English) were inevitable. The six chapters are as follows:

Chapter 2: Burkart K, Endlicher W (2011): The effect of season and meteorology on human mortality in tropical climates: A systematic review, *in preparation*.

Chapter 3: Burkart K, Endlicher W (2011): Human Bioclimate and Thermal Stress in the Megacity of Dhaka, Bangladesh – A Climatological Approach to Health Relevance Assessment. Krämer A, Khan MMH, Kraas F (Eds.). Health in Megacities and Urban Areas. Springer. Heidelberg, *in press*.

Chapter 4: Burkart K, Endlicher W (2009): Assessing the Atmospheric Impact on Public Health in the Megacity of Dhaka, Bangladesh. Die Erde 140 (1): 93-109.

Chapter 5: Burkart K, Khan MH, Krämer A, Breitner S, Schneider A, Endlicher W (2011): Seasonal variations of all-cause and cause-specific mortality by age, gender, and socio-economic condition in urban and rural areas of Bangladesh. International Journal for Equity in Health, *submitted*.

Chapter 6: Burkart K, Breitner S, Schneider A, Khan MH, Krämer A, Endlicher, W (2011): The effect of atmospheric thermal conditions and urban thermal pollution on all-cause and cardiovascular mortality in Bangladesh. Environmental Pollution, *in press*.

Chapter 7: Burkart K, Endlicher W (2011): Age-specific analysis of short- and long-term meteorological effects on mortality in Bangladesh, *in preparation*.

Three appendices supplement the thesis:

Appendix 1: Supplementary Material provided with the manuscript "Burkart K, Khan MH, Krämer A, Breitner S, Schneider A, Endlicher W (2011): Seasonal variations of all-cause and cause-specific mortality by age, gender, and socio-economic condition in urban and rural areas of Bangladesh. International Journal for Equity in Health, *submitted.*"

Appendix 2: Supplementary Material provided with the manuscript "Burkart K, Breitner, S, Schneider A, Khan MH, Krämer A, Endlicher W (2011): The effect of atmospheric thermal conditions and urban thermal pollution on all-cause and cardiovascular mortality in Bangladesh. Environmental Pollution, *in press.*"

Appendix 3: Supplementary Material provided with the manuscript "Burkart K, Endlicher W (2011): Age-specific analysis of short- and long-term meteorological effects on mortality in Bangladesh, *in preparation.*"

1.4 THE AUTHORS' CONTRIBUTION TO THE INDIVIDUAL PAPERS (CHAPTER 2-7)

Chapter 2: I designed the systematic literature review, conducted the literature search, reviewed and analysed the relevant research, and wrote the entire manuscripts. Wilfried Endlicher critically reviewed the manuscript and advised me in the whole process.

Chapter 3: I designed the research concept in cooperation with Wilfried Endlicher. I reviewed the relevant literature, analysed and interpreted the data. Furthermore, I wrote the entire manuscript. Wilfried Endlicher critically reviewed the manuscript and advised me in the whole process.

Chapter 4: I developed the study design in cooperation with Wilfried Endlicher. Moreover, I reviewed the relevant literature, analysed and interpreted the data and wrote the entire manuscript. Wilfried Endlicher critically reviewed the manuscript and advised me in the whole process.

Chapter 5: I developed the research design and analytical approach, performed the statistical analysis, and wrote the entire the manuscript. Wilfried Endlicher, Mobarak Hossain Khan and Alexander Krämer assisted with the research design and critically reviewed the manuscript and discussed the findings and interpretation. Moreover, Wilfried Endlicher advised me in the whole process. Susanne Breitner and Alexandra Krämer contributed to the statistical analysis and critically reviewed the manuscript and discussed the findings and interpretation. All authors have read and approved the final manuscript.

Chapter 6: I developed the research design and analytical approach, performed the statistical analysis, and wrote the entire the manuscript. Wilfried Endlicher, Mobarak Hossain Khan and Alexander Krämer assisted with the research design and critically reviewed the manuscript and discussed the findings and interpretation. Moreover, Wilfried Endlicher advised me in the whole process. Susanne Breitner and Alexandra Krämer contributed to the statistical analysis and critically reviewed the manuscript and discussed the findings and interpretation. All authors have read and approved the final manuscript.

Chapter 7: I developed the study design and analytical approach, conducted the data analysis, interpreted the findings and wrote the entire manuscript. Wilfried Endlicher critically reviewed the manuscript and advised me in the whole process.

CHAPTER 2: THE EFFECTS OF SEASONS AND METEOROLOGY ON HUMAN MORTALITY IN TROPICAL CLIMATES: A SYSTEMATIC REVIEW

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ABSTRACT

A multitude of studies have assessed the health-atmosphere relationship in industrialised countries of the mid-latitudes. However, to date, little scientific knowledge about the short- or long-term impact of atmospheric conditions on human mortality exists for tropical regions. Within the scope of this systematic literature review, we searched and compiled original research studies on the impact of seasonal and meteorological effects on mortality in the tropics, following predefined inclusion and exclusion criteria. In total, 28 studies on seasonality and 6 studies on meteorological effects were identified and systematically analysed. Findings indicate that mortality generally increases during the rainy season in most tropical regions. Nevertheless, some exceptions from this wide-ranging pattern were found. In studies that investigated meteorological effects, increased mortality was observed at the high and low ends of the temperature range, with the effects of cold temperatures outweighing those of elevated temperatures in most cases. Both seasonal and meteorological effects were subject to population-specific factors, such as age and socio-economic status. The public health relevance and implications of existing research and findings were discussed, particularly against the background of climate change and ongoing worldwide urbanisation processes.

2.1 INTRODUCTION

2.1.1 Systematic literature review

The objective of a systematic literature review is to identify, appraise, select and synthesise all high-quality research evidence relevant to a particular research question. Although it is difficult to make generalisations based on an individual article, a (systematic) review can provide a clearer and more consistent picture about a particular topic of interest (Davies and Crombie 2001; Egger et al. 2001; Pai et al. 2004). A systematic review is a well-established research method, particularly in medicine but also in other disciplines such as psychology and sociology. In contrast to common literature reviews, a systematic review is led by a peer-reviewed protocol such that its outcomes can be reproduced. While common literature reviews are easily subject to some subjectivity, a systematic review is meant to overcome this deficiency. A well-defined research question containing inclusion and exclusion criteria for the literature search are explicitly pre-defined. The aim of the present systematic review conducted within the scope of this thesis was to compile a comprehensive inventory of all the relevant literature on seasonal and meteorological effects on mortality in tropical climates. Findings were systematically extracted, analysed and discussed to identify research needs and to discuss the empirical research findings of the thesis.

2.1.2 Evidence of seasonal and meteorological effects from industrialised countries

The association between atmospheric conditions and health has been recognised by a multitude of scientists. The first inquiries into this subject date back to the Greek physician Hippocrates, who targeted the effect of 'season' and 'airs' on the human organism in his work "Airs, Waters, and Places". Later, the scientist Alexander von Humboldt acknowledged the influence of climatic and metrological conditions on the human organism. Since then, numerous studies on this topic have been conducted (Basu and Samet 2002; Basu 2009). Scientific interest in the effects of atmospheric conditions on human health has recently resurged due to the projected consequences of climate change. To date, most of these studies have focused on industrialised regions of the mid-latitudes (e.g., Europe, North America or Japan). Generally, studies investigating atmospheric effects can be separated into two groups: studies that assess seasonal effects on mortality (mid- to long-term effects ranging from several weeks to several months) and studies that assess the effects of meteorological conditions (e.g., temperature, humidity and rainfall) on mortality (short- to mid-term effects ranging from a few days to several weeks). Although atmospheric effects are not directly assessed in seasonality analysis, seasonal mortality variations are primarily thought to be caused by varying meteorological conditions. Recent seasonality studies in temperate climates have revealed higher mortality rates in winter compared to summer (Rau 2006). In European countries, excess mortality during the cold season ranged between 10% and 30% (ibid). Research further revealed that the seasonal pattern has changed over recent centuries (Sakamoto-Momiyama 1978; Rau 2006). In developed countries, a shift from a summer peak in mortality towards a winter peak has been observed (ibid). In addition to the dependence of seasonal mortality fluctuations on the prevailing burden of disease, there are other non-atmospheric factors (e.g., cultural or behavioural aspects or socio-economic conditions), that can modify seasonal patterns of mortality. This effect is well demonstrated by the existence of various seasonality patterns within the same climatic region. For instance, major differences were observed between urban and rural areas in France in the 18th century (Bideau et al. 1988) or between White and Afro-American groups in Philadelphia, USA (Klepp 1994). Moreover, in South Africa, seasonal variations differed between ethnic groups. A high burden of diarrhoeal disease led to a mortality peak during the hot season among the black and coloured populations, whereas the predominance of other diseases led to a peak during the cold season among the White and Asian populations (Crook and Dyson 1981). In a more recent study, education was mentioned as a determinant of seasonal fluctuations in mortality in the United States of America (Rau 2006).

Regression analysis of temperature effects on mortality has revealed a ‘U’- or ‘V-shaped temperature-mortality relationship in industrialised countries, with increased mortality at both low and high temperatures (Basu and Samet 2002; Basu 2009). Although the overall effect of low temperatures on mortality predominates in mid-latitude countries, a sharper rise of mortality at high temperatures than at low temperatures has been observed (Basu and Samet 2002; Basu 2009). Heat waves, as the heat waves in Chicago in 1995 or in Europe in 2003 have caused tremendous excess mortality and have been recognised among the most fatal natural disasters (Schär and Jendritzky 2004; Kaiser et al. 2007; Robine et al. 2007). A study analysing the temperature-mortality relationship in 50 cities of the United States showed that heat effects were strongest in cities with milder summers, less air conditioning and higher population density (Medina-Ramón and Schwartz 2007). Likewise, Hajat et al. (2005) found different dose-response relationships between heat and mortality in Delhi, São Paulo and London. They, moreover, reported different impacts of heat on mortality in the cities of London, Milan and Budapest (Hajat et al. 2005). Smoyer et al. (2000) found the strongest relationship between heat and mortality in Southern Ontarian cities with relatively high urbanisation and a high cost of living. In Berlin, mortality rates were found to correlate well with the distribution of sealed surfaces (Gabriel and Endlicher 2011). During the Chicago heat wave of 1995, poor urban populations, people with fewer social connections and Afro-Americans had the most elevated mortality risk (Klinenberg 2002; Kaiser et al. 2007).

Given the dynamic and complex nature of seasonal and meteorological effects on mortality, as illustrated above, comprehensive analyses are necessary to understand how to most efficiently target health interventions. Understanding the relationship between seasonality, weather and mortality is particularly important to control and mitigate the impact of the projected consequences of global warming. The objectives of this systematic review were to compile all relevant publications conducted in tropical regions and to systematically assess and analyse the findings published in these studies. We were particularly interested in age- and population-specific differences, effect modifications arising from non- atmospheric influences and temporal changes.

2.2 METHODOLOGY

2.2.1 Inclusion and exclusion criteria

A literature search was conducted using the PubMed database. We limited our search to articles written in English, Spanish and French, and those relevant to the human species. For the database query, we combined the keyword “mortality” with the following terms[6]: “temperature”, “weather”, “climate”, “cold”, “heat”, “meteorological”, “meteorology”, “atmospheric”, “atmosphere”, and ”season”. We selected all original research papers dealing with seasonality or meteorological effects in the tropics (please see 2.2 for definition of the tropics). Eco-epidemiological studies based on (sample) vital registration systems or based on hospital statistics were included. Case studies and laboratory results were not included. We considered studies that featured descriptive analyses, time-series analyses, regression modelling, or case-crossover approaches. We did not limit our inclusion criteria to any particular effect (e.g., solely heat effects or a particular time frame); rather, we compiled all research conducted in the regions of interest. The database search conducted in August 2010 returned 13,825 hits, of which 300 were selected based on their title and abstract. We excluded 280 articles because they were not related to our study locations. Thus, we obtained 20 articles that met the search criteria. Searching the reference lists of the 20 identified articles rendered another 14 relevant articles. In total, we identified 34 articles for our review, of which 28 were

[6] PubMed query syntax: (mortality AND temperature) OR (mortality AND weather) OR (mortality AND climate) OR (mortality AND cold) OR (mortality AND heat) OR (mortality AND meteorological) OR (mortality AND meteorology) OR (mortality AND atmospheric) OR (mortality AND atmosphere) OR (mortality AND season)

related to seasonal effects on mortality and 6 were related to meteorological effects. Figure 2.1 illustrates the database search and the inclusion and exclusion steps that were followed.

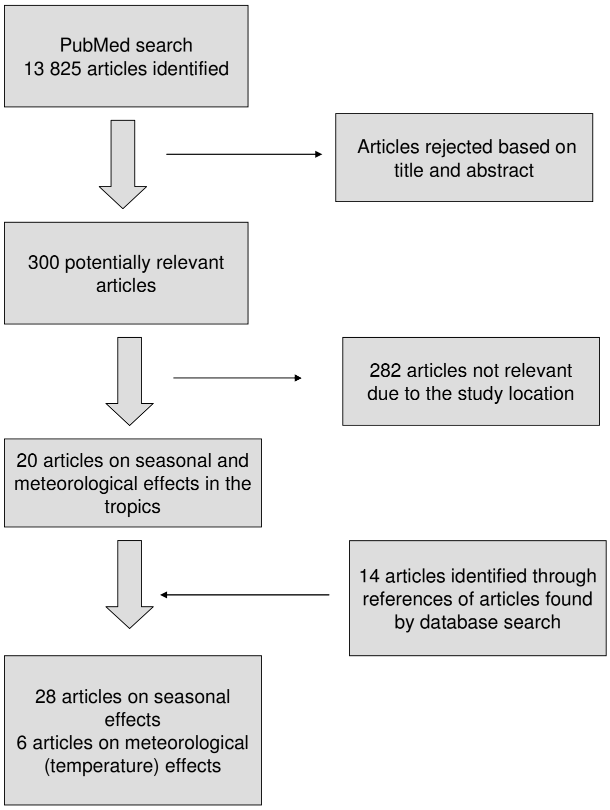

Figure 2.1: Schematic illustration of literature search and inclusion/exclusion steps

2.2.2 Defining tropical climates

There are several ways to define climate zones: by latitude and solar climatological criteria or by effective and genetic classification criteria. According to a solar climatological classification, the tropics are located between 23.5° north and 23.5° south of the equator. To account for effective climatic conditions, regions are often classified by so-called effective climate classifications. Of all the available methods, perhaps the most commonly used is the Köppen-Geiger classification. Although the classification scheme was developed in the first half of the twentieth century, it still meets the needs of modern climate science (Essenwanger 2001; Kraus 2004). It has recently been applied to climate model predictions (Lohmann et al. 1993; Kleidon et al. 2000) and is likely to be used in future simulations and models (Kottek et al. 2006). To date, a shift in the distribution and extension of the Köppen-Geiger climate zones – with an expansion of type 'B" climates – has already been observed, demonstrating the ongoing climate change (Gerstengarbe and Werner 2009).

Table 2.1: Köppen-Geiger climate types and classification criteria

Type	Description	Criterion
A	**Equatorial climates**	$T_{min} \geq +18°C$
A_f	Equatorial rainforest, fully humid	$P_{min} \geq 60$ mm
A_m	Equatorial monsoon	$P_{ann} \geq 25(100-P_{min})$
A_s	Equatorial savannah with dry summer	$P_{min} < 60$mm in summer
A_w	Equatorial savannah with dry winter	$P_{min} < 60$mm in winter
B	**Arid climates**	$P_{ann} < 10\ P_{th}$
B_S	Steppe climate	$P_{ann} > 5\ P_{th}$
B_W	Desert climate	$P_{ann} \leq 5\ P_{th}$
C	**Warm temperate climates**	$-3°C < T_{min} < +18°C$
C_s	Warm temperate climate with dry summer	$P_{smin} < P_{wmin}$, $P_{wmax} > 3\ P_{smin}$ and $P_{smin} < 40$mm
C_w	Warm temperate climate with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10\ P_{wmin}$
C_f	Warm temperate climate, fully humid neither C_s nor C_w	
D	**Snow climates**	$T_{min} \leq -3°C$
D_s	Snow climate with dry summer	$P_{smin} < P_{wmin}$, $P_{wmax} > 3\ P_{smin}$ and $P_{smin} < 40$mm
D_w	Snow climate with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10\ P_{wmin}$
D_f	Snow climate, fully humid neither D_s nor D_w	
E	**Polar climates**	$T_{max} < +10°C$
E_T	Tundra climate	$0°C \leq T_{max} < +10°C$
E_F	Frost climate	$T_{max} < 0\ °C$

T_{ann} is the annual mean near-surface (2m) temperature
T_{max} and T_{min} are the monthly mean temperatures of the warmest and coldest months by
P_{ann} is the accumulated annual precipitation
P_{min} is the precipitation of the driest month
P_{smin}, P_{smax}, P_{wmin} and P_{wmax} are the lowest and highest monthly precipitation values for the summer and winter half-years on the hemisphere considered

Köppen (1900) constructed five zones based on thermal criteria: the equatorial/tropical zone (A), the arid zone (B), the warm temperate zone (C), the snow zone (D), and the polar zone (E). The sub-classification (indexed by second and subscript letter) of these zones is based on additional thermal criteria and hydrological factors (Köppen 1900; Geiger 1954). Between 23.5° north and 23.5° south, climate types 'A', 'B' and 'C' can be found. Type 'A' climates can be considered classical tropical climates with constantly elevated temperatures and high amounts of precipitation. In close proximity to the equator, type ‘A’ climates are usually fully humid (A_f). Moving north and south towards the 23.5° latitudes, precipitation decreases, and a type of dry season emerges as regions get affected by the subtropical high pressure system (A_w). With the growing influence of this high pressure system, climates become increasingly dryer, and the crossover from type ‘A’ to type ‘B’ climates (arid climates) takes place. In addition to these latitude-dependent climate variations, elevation plays a crucial role. Regions situated at high altitudes exhibit lower temperatures and are therefore usually classified as having warm temperate type ‘C’ climates. Table 2.1 presents an overview of climate types including underlying sub-classification criteria according to Köppen and Geiger. For the purpose of this review, tropical regions were defined based on a solar definition, selecting all regions situated between the 23.5° northern and southern latitudes. We also classified study regions by the Köppen-Geiger system due to its relevance.

2.3 RESULTS

2.3.1 Studies of seasonal effects on mortality

In total, 28 studies investigating seasonal variations in mortality were included in this review (Table 2.2). Countries in Africa, South and Central America, and South and Southeast Asia were included. An overview of the spatial distribution of study areas is given in the map (Figure 2.2). Most data were collected during the second half of the 20th century, with one study from the second half of the 19th century and one study from the first half of the 20th century. More rural areas were investigated compared to urban areas. The research approaches ranged from descriptions of (monthly) death counts and estimations of mortality rates and odds ratios to more sophisticated methodologies such as time series and regression analysis. Several studies stratified samples by cause of death, age, sex, or socio-economic status (Table 2.2). Temperature and precipitation were mainly discussed as potential drivers of seasonal fluctuations. However, socio-economic and behavioural factors were also considered briefly.

2.3.1.1 All-cause and cause-specific seasonality[7]

In Gambia (type 'A' to type 'B' climate transition region), six studies comprising data from the 1950s to the 1990s were assessed (McGregor et al. 1961; Thompson and Rahman 1967; McGregor et al. 1970; Brewster and Greenwood 1993; Jaffar et al. 1997; Rayco-Solon et al. 2004). For all considered causes of death (infectious diseases, malaria, acute respiratory infections, acute gastroenteritis, malnutrition and septicaemia) and age groups, a peak was observed during the rainy season. In Gambia, the rainy season is accompanied by increased temperatures and coincides with the hungry season, when depletion of the food supply is at its peak. In Senegal (type 'B' climate), all-cause mortality and cause-specific mortality (diarrhoea, acute respiratory infection, malaria, fever of unknown origin, other causes), with the exception of meningitis-related mortality, peaked during the rainy season in September and October (Cantrelle et al. 1980; Delaunay et al. 2001; Etard et al. 2004). However, age stratification revealed a modified pattern and will be discussed in *2.3.1.2*. In Nigeria (type 'A' climate), a higher risk of death was observed during the rainy season (Lawoyin 2001). In a slum in Nairobi, Kenya (type 'C' climate), peaks in all-cause and pneumonia-related under-five mortality were observed at the end of the rainy season and at the beginning of the cold season. The lowest mortality levels occurred during the second least intensive period of rain, when temperatures were higher (Ye et al. 2009; Mutisya et al. 2010).

[7] The results presented in this section reflect a general distribution of all-cause and cause-specific seasonality without further stratification by age or any other factor. However, some studies solely considered a particular age group (e.g., children). In those cases, we indicate that the results apply to that particular group.

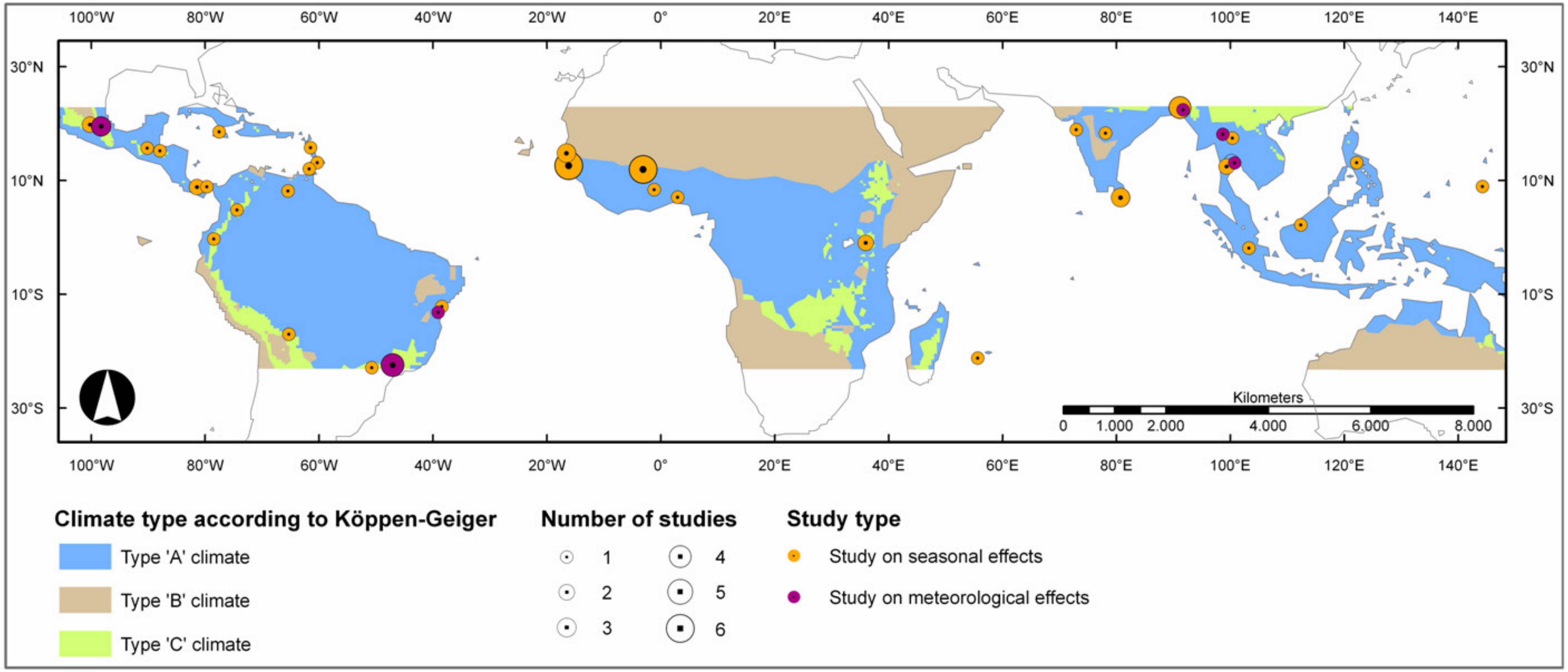

Figure 2.2: Spatial distribution of studies conducted in the tropics between the 23.5° northern and southern latitudes (coloured area). ***(Data source: Kottek et al. 2006; this study)***

Contrary to the seasonal pattern described above, in Burkina Faso (type ‘B’ climate), all-cause and cardiovascular mortality were highest during the dry and hot season from February to April (Kynast-Wolf et al. 2002; Sankoh et al. 2003; Kynast-Wolf et al. 2006; Kynast-Wolf et al. 2010). Age stratification showed a more complex pattern with deviations from the general distribution. Age-specific findings are discussed in *2.3.1.2*.

Four comprehensive studies assessing the seasonality of mortality have been published in Matlab, Bangladesh (type ‘A’ climate). All the studies relied on data from the 1970s and 1980s collected within a registration system established by the International Centre for Diarrhoeal Disease Research, Bangladesh (ICDDR,B). All-cause mortality, respiratory deaths and deaths from other causes peaked during the cold and dry winter seasons, whereas fever, tetanus, measles, and injuries peaked during the warm and rainy seasons. For the period of 1972–1974, winter peaks in dysentery and chronic diarrhoea were observed with no significant seasonal variation in acute diarrhoea. In contrast, for the period of 1982–1990, a peak in diarrhoeal deaths in general and in watery diarrhoea in particular was observed during the rainy season. Age stratification revealed a modified pattern and will be discussed in *2.3.1.2.* In Bombay, India, infant mortality was highest during the rainy season in the 1960s (Ruzicka and Kanitkar 1973). In Colombo as well as in Nuwara-Eliya, Sri Lanka, seasonal variations in all-cause mortality were associated with variations in rainfall and humidity (Motohashi et al. 1996). The highest levels of mortality were observed during the rainy season with a one-month lag. Likewise, in Guam, an island in the Pacific, seasonal fluctuations in the first half of the 20th century were closely related to rainfall patterns, with maximum levels during the rainy season (Underwood 1991). Peaks in all-cause mortality and mortality from gastrointestinal causes during the early months of the rainy season were also observed in Escazú, Costa Rica (type ‘A’ climate), whereas respiratory mortality showed little fluctuation (Madrigal 1994).

McMichael et al. (2008) found only modest seasonal variations in all-cause mortality for Chiangmai, and Bangkok in Thailand and Salvador, Brazil, whereas São Paulo, Brazil, and Mexico City, Mexico, which are both categorised as moderate type C climates, showed peaks during the cold and dry seasons. Crook and Dyson (1981) analysed unstratified data from 22 tropical countries. Their findings were quite diverse. No seasonal fluctuations were observed in Honduras, Guatemala, Venezuela, Sri Lanka, Malaysia, and Thailand. A peak associated with the rainy season was observed in Ghana, Barbados, Dominica, Jamaica, Trinidad and Tobago, Panama, Paraguay, Ecuador, Bolivia, Colombia, and India. A peak during the dry season was observed in Mauritius, Costa Rica, and Mexico, and double peaks during the rainy and dry seasons were found in the Philippines. All investigated regions were in tropical type 'A' climates, but there was a variety of subtypes, and several countries had multiple subtypes. Singapore (type 'A_f' climate) exhibited a peak in May and June, although the amount of precipitation and the temperature were consistently high throughout the year.

2.3.1.2 Age effects and vulnerable subgroups

Age was found to be a determining factor in shaping the seasonal pattern. On the one hand, age influenced the magnitude of seasonal fluctuations, but on the other hand, some age groups exhibited an essentially different seasonal pattern than the general population. Generally, children and the elderly were more affected by seasonal effects compared to other age groups (Becker 1981; Becker and Weng 1998; Rayco-Solon et al. 2004; Becher et al. 2008; Kynast-Wolf et al. 2010).

Particularly complex seasonal variations were found for infants. In Senegal, mortality in children less than 18 months old was highest at the end of the rainy season, but in children over 18 months old, mortality was highest during the dry season (Cantrelle et al. 1980). In Burkina Faso, infant mortality peaked at the end of the rainy season, although overall mortality was highest during the dry season. Children from one to four years showed an intermediate pattern of mortality fluctuations, with the highest rates at the end of the rainy season but additionally increased levels during the early dry season (Kynast-Wolf et al. 2006; Becher et al. 2008). In Bangladesh, all-cause mortality peaked during the cold season, post-neonatal mortality was highest in April (the pre-monsoon season), and child and youth mortality peaked during and at the end of the monsoon season (Becker 1981; Muhuri 1996; Becker and Weng 1998). Neonatal mortality (adjusted for births) peaked in the monsoon season in 1972-1974. Later, for the 1982-1990 period, neonatal mortality peaked at the beginning of the cold season (Becker 1981; Becker and Weng 1998).

Young and middle-aged adults generally showed no or weak seasonal variations (Becker 1981; Becker and Weng 1998; Rayco-Solon et al. 2004; Kynast-Wolf et al. 2010). For the elderly, seasonal variations were quite evident (Becker 1981; Becker and Weng 1998; Kynast-Wolf et al. 2006; Kynast-Wolf et al. 2010). For instance, in Burkina Faso, malaria mortality among the elderly peaked during the dry season, although malaria mortality generally peaked in the rainy season (Hammer et al. 2006; Becher et al. 2008).

Only a few studies assessed the effect of socio-economic conditions on seasonal or meteorological effects on mortality. Muhuri (1996) found decreased seasonal variations in a treatment area in which health interventions were undertaken compared to a comparison area. Moreover, the author found an increased risk of mortality, and particularly diarrhoeal mortality, if the mother had no schooling. Rayco-Solon (2004) did not find differences in seasonal fluctuations between sexes.

2.3.1.3 Temporal changes

Most of the studies were based on short-term time series and lasted no more than a couple of years. Only a few studies analysed long-term changes in seasonality patterns, with conflicting outcomes. For instance, decreased seasonality was observed in Gambia after 1985 (Rayco-Solon et al. 2004). Madrigal (1994) analysed data from Costa Rica (Escazú) over a time period of 70 years from 1851-1921. The time series approach showed that mortality had become less seasonal in later years (1892-1921). The decreasing seasonality was attributed to a decline in deaths from gastrointestinal causes. In Senegal, decreasing seasonality was observed in the 1960s to 1980s. However, in the 1990s, seasonal fluctuations increased again, possibly due to the re-emergence of malaria. In Bangladesh, the seasonality of neonatal mortality and injury-related deaths declined, but seasonality remained pronounced for all other causes of death despite a general decline in mortality between the 1970s and the 1980s. The shape of the seasonality pattern remained unaffected there, except for a shift in the peak of neonatal mortality from the end of the rainy season to the beginning of the cold season (Becker 1981; Becker and Weng 1998).

Table 2.2: Studies assessing seasonal effects on mortality

Study	Country/ Region	Latitude/ Longitude; Elevation	Temp. [°C] Rainfall [mm] [a] Climate zone	Study period	Stratifications (causes of death, age groups, other strata)	Methods	Results
McGregor et al. (1961)	Gambia/ Keneba (rural)	13°N/16°W 35m	25.4 (23.2-27.0) 866 (0-326) (data for Banjul) A_w/B_s	5 year period	All causes; Children (<7 yrs.)	Descriptive analysis (Monthly death counts)	**Peak in rainy and warm season** from Jul-Oct (66%), peak in Aug (26%)
Jaffar et al. (1997)	Gambia/ Upper River Division (rural)	13°N/16°W 35m	25.4 (23.2-27.0) 866 (0-326) (data for Banjul) A_w/B_s	1989-1993	Acute respiratory infection, malaria, acute gastroenteritis, malnutrition, septicaemia, other causes; Infants (0-11 months), children (1-4 yrs.)	Monthly and annual death and mortality rates	**Peak in rainy and warm season** observed for all causes all ages; All-cause and cause-specific mortality peaked from Jul-Sep; All-cause mortality peaked in Sep (17%), malaria in Sep (28%), acute respiratory infections in Oct (18%), acute gastroenteritis in Aug (20%), malnutrition in Aug (20%), and septicaemia in Sep (16%)
Rayco-Solon et al. (2004)	Gambia/ Keneba, Manduar, Kantong Kunda (rural)	13°N/16°W 35m	25.4 (23.2-27.0) 866 (0-326) (data for Banjul) A_w/B_s	1950s-1975; 1975-1984 1985-1997	All-causes; Early neonates (0-7 days), late neonates (8-28 days), infants (1-11 months), children (1-4 yrs.), youths (5-14 yrs.), adults and elderly (≥15 yrs.)	Logistic regression; Odds of dying in rainy vs. hungry season	**Peak in rainy and warm season** prior to 1975 (odds=1.87;95%CI=1.62-2.17) and from 1975-1984 (odds=1.84;95%CI=1.34-2.53) **Decrease in seasonality** after 1985 (odds=1.23;95%CI=0.85-176) **Peak in rainy and warm season** for age groups 1-11 months (odds=1.53;95%CI=1.20-1.94) and 1-4 yrs. (odds=2.59;95%CI=2.12-3.14), but not for other age groups
Brewster & Green-wood (1993)	Gambia/ Banjul (urban)I	13°N/16°W 2m	25.4 (23.2-27.0) (data for Banjul) A_w/B_s	1988-1990	All-causes, diarrhoea, pneumonia, malnutrition, meningitis; Children (<12 yrs.)	Mortality rates in rainy vs. dry season; (Odds ratio)	**Peak in rainy and warm season** from Jul-Dec for all causes (OR=1.3;95%CI=1.2-1.5), diarrhoeal diseases (OR=2.1;95%CI=1.4-3.1), pneumonia (OR=1.8;95%CI=1.3-2.7), and malnutrition (OR=1.3;CI=0.9-1.9)
Thompson & Rahman (1967)	Gambia/ Keneba (rural)	13°N/16°W 35m	25.4 (23.2-27.0) 866 (0-326) A_w; (data for Banjul)	1962-1963	All-causes; Children (<5 yrs.)	*no information*	**Peak in rainy and warm season**
McGregor et al. (1970)	Gambia/ Keneba (rural)	13°N/16°W 35m	25.4 (23.2-27.0) 866 (0-326) A_w; (data for Banjul)	1962-1963	All-causes; Children (<5 yrs.)	*no information*	**Peak in rainy and warm season**
Cantrelle (1980)	Senegal/ Ngayokheme (rural)	14°N/16°W	24.4 (20.9-27.7) 505 (0-215) B_s	1963-1973	All-causes; Children (<5yrs., 0-5 months, 6-11 months, 12-17 months, 18-23 months, 24-29 months, 30-35 months)	Monthly relative risk	**Peak in rainy and warm season** observed for <5 yrs., 0-5 months, 6-11 months, 12-17 months **Peak in dry and cold season** for 18-23 months, 24-29 months, 30-35 months
Delaunay et al. (2001)	Senegal/ Sine Saloum (rural)	14°N/16°W	24.4 (20.9-27.7) 505 (0-215) B_s	1963-1999	All-causes; Infants (<1 yr.), children (1-4 yrs.)	Mortality rates	**Peak in the rainy and warm season** from Aug-Nov for all ages **Decrease of seasonality** from 1960s-1980s, but **increase of seasonality** in 1990s (re-emergence of malaria)

RR=Relative risk; OR= Odds Ratio; CI=confidence intervals
[a] The information on temperature and precipitation refer to yearly average values and monthly average minimum and maximum values as depicted in braces; the meteorological data was taken from "WorldClimate" (www.worldclimate.com)

Table 2.2: Studies assessing seasonal effects on mortality *(continued)*

Study	Country/ Region	Latitude/ Longitude; Elevation	Temp. [°C] Rainfall [mm] [a] Climate zone	Study period	Stratifications (causes of death, age groups, other strata)	Methods	Results
Etard et al. (2004)	Senegal/ Niakhar (rural)	14°N/16°W	24.4 (20.9-27.7) 505 (0-215) B_s	1989-2000	All-causes, diarrhoeal, acute respiratory infections, malaria, fever, other causes Children (<15 yrs.)	Monthly mortality rates	**Peak in the rainy and warm season** observed for all causes (Sep/Oct;16%/18%), diarrhoeal diseases (Oct;19%), acute respiratory infections (Oct;16%), malaria (Sep/Oct;26%/31%), fever (Sep/Oct;16%/16%), other causes (Oct;13%), **Peak in dry and cold season** observed for meningitis (Feb/Mar;21%/31%)
Lawoyin (2001)	Nigeria/ Lagun (rural)	7°N/ 3°E	26.5 (24.9-28.2) 1813 (22-449) A_w	1993-1997	All causes Neonates, postneonates and infants	Death counts during rainy vs. dry season (Fisher's exact test)	**Peak in the rainy and warm season** observed for infants (RR=1.62;95%;CI=0.92-2.9;p=0.103) and neonates (RR=2.69;95%CI 1.15-6.28;p=0.018).
Mutisya et al. (2010)	Kenia/Nairobi (urban slum)	1°S/36°E 1624m	19.0 (17.2-20.7) 760 (13-160) C_w	2003-2005	All causes Infants (<1 yrs.), Children (<5 yrs.)	Quarterly relative risk; Poisson regression	**Peak at the end of rainy/warm season and beginning of cold season**; Highest mortality risk in second (RR=1.6;95%CI=1.1-2.2) and third quarter (RR=1.5;95%CI=1.1-2.1) of the year compared to fourth forth quarter for infants and <5 yrs.
Ye et al. (2009)	Kenia/Nairobi (urban slum)	1°S/36°E 1624m	19.0 (17.2-20.7) 760 (13-160) C_w	2003-2005	Pneumonia, other causes Children (<5 yrs.)	Quarterly relative risk; Poisson regression	**Peak at the end of rainy/warm season and beginning of cold season**; Pneumonia mortality was highest during the second (RR=2.1;95%CI=1.1-3.9) and third quarter of the year (RR=1.9;95%CI=1.0-3.6) compared-the fourth quarter, with higher mortality during cold months and lower mortality during the warm months
Kynast-Wolf et al. (2002)	Burkina Faso/ Nouna district (mostly rural)	12°N/3°W 309 m	28.3 (32.6-24.8) 786 (0-224); B_s (data for Ouagadougou)	1993-1998	All-cause All ages	Age-adjusted mortality rates; Poisson regression	**Peak in dry and hot season** from Nov-May (peak in Feb)
Sankoh et al. (2003)	Burkina Faso/ Nouna district (rural)	12°N/3°W 309 m	28.3 (32.6-24.8) 786 (0-224); B_s (data for Ouaga-dougou)	1993-1998	All-causes Adults (15-59), elderly (≥60 yrs.)	Crude death rate; Poisson regression	**Peak in dry and hot season** observed for adults and elderly; Secondary peak in Sep (end of rainy season) for both age groups
Kynast-Wolf et al. (2006)	Burkina Faso/ Nouna district (mostly rural)	12°N/3°W 309 m	28.3 (32.6-24.8) 786 (0-224); B_s (data for Ouagadougou)	1993-2001	All-causes Infants (<1 yr.), children (1-4 yrs.), youths (5-14 yrs.), adults (15-59 yrs.), elderly (≥60 yrs.)	Mortality rates; Poisson regression	**Peak in dry and hot season** for all-causes and all age groups, except infants and children **Peak at the end of the rainy season** for infants; **Peak at the end of the rainy season and beginning of dry season** for children (1-4 yrs.)

RR=Relative risk; OR= Odds Ratio; CI=confidence intervals
[a] The information on temperature and precipitation refer to yearly average values and monthly average minimum and maximum values as depicted in braces; the meteorological data was taken from "WorldClimate" (www.worldclimate.com)

Table 2.2: Studies assessing seasonal effects on mortality *(continued)*

Study	Country/ Region	Latitude/ Longitude; Elevation	Temp. [°C] Rainfall [mm] [a] Climate zone	Study period	Stratifications (causes of death, age groups, other strata)	Methods	Results
Hammer et al. (2006)	Burkina Faso/ Nouna district (rural/urban)	12°N/3°W 309 m	28.3 (32.6-24.8) 786 (0-224); B_s (data for Ouagadougou)	1999-2003	All-causes, malaria Children (<5 yrs.)	Relative risk in dry vs. rainy season	**Higher relative risk in dry and hot season** for all causes (RR=0.83;95%CI=0.75-0.92) and malaria (RR=0.57;95%CI=0.49-0.66)
Becher et al. (2008)	Burkina Faso/ Nouna district (rural/urban)	12°N/3°W 309 m	28.3 (32.6-24.8) 786 (0-224); B_s (data for Ouagadougou)	1999-2003	Malaria, other causes Infants (<1 yr.), children (1-4 yrs.), elderly (≥60 yrs.)	Age-specific death rates; Poisson regression (sine function)	**Peak in rainy and cold season** observed for malaria and other causes in infant and children **Peak in dry and hot season** observed for malaria and other causes in elderly
Kynast-Wolf et al. (2010)	Burkina Faso/ Nouna district (rural/urban)	12°N/3°W 309 m	28.3 (32.6-24.8) 786 (0-224); B_{sh} (data for Ouagadougou)	1999-2003	All-causes, cardiovascular Adults (40-65 yrs.), elderly (≥65 yrs.)	Age-specific death rates; Poisson regression	**Peak in dry and hot season** observed for all causes in elderly
Becker (1981)	Bangladesh/ Matlab	23°N/91°E	25.6 (18.3-29.1) 1997 (8-399) A_w	1972-1974	Fever, acute diarrhoea, dysentery and chronic diarrhoea, respiratory diseases, pox and measles, accidents, takuria (tetanus), others Neonates (0-29 days), postneonates (30-364 days), children (1-4 yrs.), youths (5-14 yrs.), adults (15-44 yrs.), elderly (≥45 yrs.)	Trigonometric regression (sine function)	**Peak in cold and dry season** observed for dysentery and chronic diarrhoea (Dec), other causes (Dec), and ≥45 yrs. (Dec) **Peak in rainy and warm season** observed for accidental causes, neonates, (Aug), tetanus (Sep/Oct), post-neonates (Apr) **No significant pattern was found** observed for all-causes, fever, respiratory diseases, smallpox and measles
Becker & Sardar (1981)	Bangladesh/ Matlab	23°N/91°E	25.6 (18.3-29.1) 1997 (8-399) A_w	1972-1974	All-causes, fever, dysentery, respiratory, tetanus, other causes All ages, neonates (0-29 days), children (1-4 yrs.), youths (5-14 yrs.), adults (15-44 yrs) Socioeconomic status	Mortality rates; Trigonometric regression (sine function)	**Peak in cold and dry season** observed for all causes (Nov/Dec), and ≥45 yrs. (Nov/Dec) **Peak in rainy and warm season** observed for fever (May/Jun), dysentery (May/Jun), tetanus (May-Oct) neonates (Jun/Aug), postneonates (Apr) **No seasonality** for other causes, respiratory causes, 4-15 yrs., 15-44 yrs. **No socioeconomic effect** on neonatal mortality; Postneonatal deaths affected by education and occupation (reduced seasonality). For elderly (≥45 yrs.) with low occupational status peak in Apr

RR=Relative risk; OR= Odds Ratio; CI=confidence intervals
[a] The information on temperature and precipitation refer to yearly average values and monthly average minimum and maximum values as depicted in braces; the meteorological data was taken from "WorldClimate" (www.worldclimate.com)

Table 2.2: Studies assessing seasonal effects on mortality *(continued)*

Study	Country/ Region	Latitude/ Longitude; Elevation	Temp. [°C] Rainfall [mm] [a] Climate zone	Study period	Stratifications (causes of death, age groups, other strata)	Methods	Results
Becker & Weng (1998)	Bangladesh/ Matlab (rural)	23°N/91°E	25.6 (18.3-29.1) 1997 (8-399) A_w	1982-1990	All-causes, injuries, respiratory, diarrhoea, other causes Neonates (0-29 days), post-neonates (30-364 days), 1-4 yrs., 5-14 yrs., 15-44 yrs., 45-64 yrs., ≥65 yrs.	Death counts/ mortality rates; Trigonometric regression (sine function)	**Peak in cold and dry season** observed for total deaths (Nov), respiratory deaths (Jan), other causes (Dec), neonates (Nov), age group of 5-14 yrs.(Oct), age group 45-64 yrs. (Dec), ≥65 yrs. (Dec) **Peak in rainy and warm season** for injury deaths (Jul); diarrhoeal deaths (Jul), post-neonates (Apr), children (1-4 yrs.) (Jul) **No seasonal pattern** observed for the age group 15-44 yrs.
Muhuri (1996)	Bangladesh/ Matlab (rural)	23°N/91°E	25.6 (18.3-29.1) 1997 (8-399) A_w	1982-1987	Dysentery, diarrhoea, drowning, measles, fever, respiratory diseases Diarrhoeal vs. non-diarrhoeal mortality Children (1-4 yrs.) 2 cohorts (Treatment area with health interventions and comparison area)	Monthly mortality rates; multinomial logistic regression	**Peak at the end of rainy/warm season and beginning of cold season** observed for dysentery (Sep-Nov), drowning (Sep) **Peak at the end of rainy/warm season and beginning of cold season and secondary peak in hot premonsoon season** for all causes (Sep-Nov;Apr), watery diarrhoea (Nov/Dec;Apr), respiratory causes (Sep;Apr) **Peak in premonsoon season** observed for measles (Apr;Feb), fever (April) **Socioeconomic effects:** increased risk of mortality and particularly diarrhoeal mortality observed in post-monsoon and hungry season (Sep/Oct) if mothers had no schooling. In the treatment area seasonal variations were diminished
Ruzicka & Kanitkar (1973)	India/Bombay (Mumbai) (urban)	19°N/73°E 11m	27.2 (24.2-30.0) 2129 (0.6-647) A_w	1963-1967	All causes Infants (0-6 days, 0-27 days, 28-365 days)	Descriptive analysis (Monthly mortality)	**Peak in rainy and warm season** for 0-6 days(Jul-Sep) and 7-28 days old (Jul-Sep), for 28-365 days (May-Aug)
Motohashi et al. (1996)	Sri Lanka/ Colombo (urban)	7°N/79°E 7m	26.8 (26.0-27.8)/ 2242(64-335) A_f	1976-1980	All-causes All ages	Power spectrum analysis (of the fast Fourier transformation analysis)	Colombo: **Peak in season with maximum rainfall** (Jun/Nov;6-month periodicity)
	Sri Lanka/ Nuwara-Eliya (urban)	7°N/80°E 1890m	15.1(14.0-16.5)/ 2233(62-278) C_f	1976-1980			Nuwara-Eliya: **Peaks associated with maximum rainfall** (3-month periodicity in addition-6-months periodicity)
Madrigal (1994)	Costa Rica/ Escazú (rural/urban)	9°N/84°W 1100m	19.9 (19.1-20.6) 1873 (5-326) A_w	1851-1921	All causes, respiratory, gastrointestinal	Monthly deaths; Chi-Square and Freedman test; Box-Jenkins time series analysis	**Peak at the beginning of the rainy season** observed for gastrointestinal deaths (May-Jul). **Decrease of seasonality over time**

RR=Relative risk; OR= Odds Ratio; CI=confidence intervals
[a] The information on temperature and precipitation refer to yearly average values and monthly average minimum and maximum values as depicted in braces; the meteorological data was taken from "WorldClimate" (www.worldclimate.com)

Table 2.2: Studies assessing seasonal effects on mortality *(continued)*

Study	Country/ Region	Latitude/ Longitude; Elevation	Temp. [°C] Rainfall [mm] [a] Climate zone	Study period	Stratifications (causes of death, age groups, other strata)	Methods	Results
Underwood (1991)	Guam (Pacific island) (rural/urban)	13°S/144°E 77m	27.3(26.5-28.0)/ 2184 (63-355) A_f	1901-1941	All causes All ages	Mortality rates	**Peak in the rainy and warm season** observed for infants and children
Mc-Micheal et al (2008)	Mexico/ Mexico City (urban)	19°N/99°W 2240m	17.2 (12.8-21.2) 634 (5-129) C_w	1994-1998	All causes All ages	Daily deviation from average mortality	Mexico City: **Peak in the cold/dry season**
	Thailand/ Chiangmai (urban)	18°N/99°E 512m	26.3 (20.7-30.4) 1180 (7-233) A_w	1995-1997			Chiangmai: **No clear seasonal pattern**
	Thailand/ Bangkok (urban)	13°N/100°E 12m	28.9 (25.8-32.3) 1507 (8-344) A_w	1991-1992			Bangkok: **No clear seasonal pattern**
	Brazil/ Salvador (urban)	12°S/38°W 8m	26.1 (23.3-28.7) 2022 (107-299) A_f	1996-1999			Salvador: **No clear seasonal pattern**
	Brazil/São Paulo (urban)	23°S/46°W 800m	20.3 (13.9-25.3) 1458 (44-233) C_f	1991-1994			São Paulo: **Peak in the cold/dry season (Jul)**
Crook & Dyson (1981)	Ghana	8°N/1°W	A_w	1976	All causes All ages	Monthly relative risk (Death counts in a particular month divided by monthly average counts); Seasonality Index	**Moderate seasonal fluctuations** with peak in Jun/Jul and Dec (rainy/cold season)
	Mauritius	20°S/58°E	$A_f/A_m/A_w$	1974-1976			**Moderate peak in dry and cold season** (Aug)
	Barbados	13°N/60°W	A_w	1957-1959			**Peak in rainy and warm season** (Sep/Oct)
	Dominica	15°N/61°W	A_f/A_w	1960-1962			**Peak at beginning and end of rainy season** (Jun/Jul;Jan/Feb)
	Jamaica	18°N/77°W	A_w	1959-1962			**Peak at beginning and end of the rainy season** (May/Jun;Dec/Jan)
	Trinidad & Tobago	11°N/61°N	A_m	1972-1974			**Peak at end of the rainy season** (Jan/Dec)
	Costa Rica	10°N/84°W	A_w	1965-1973			**Peak at beginning of dry and cold season** (Jan)
	Honduras	15°N/87°W	A_w	1971-1973			**No seasonal fluctuation**
	Guatemala	15°N/90°W	A_m/A_s	1958-1959			**No seasonal fluctuation**

RR=Relative risk; OR= Odds Ratio; CI=confidence intervals
[a] The information on temperature and precipitation refer to yearly average values and monthly average minimum and maximum values as depicted in braces; the meteorological data was taken from "WorldClimate" (www.worldclimate.com)

Table 2.2: Studies assessing seasonal effects on mortality *(continued)*

Study	Country/ Region	Latitude/ Longitude; Elevation	Temp. [°C] Rainfall [mm] [a] Climate zone	Study period	Stratifications (causes of death, age groups, other strata)	Methods	Results
Crook & Dyson (1981)	Mexico	19°N/99°W	A/B/C	1971-1973	All causes All ages	Monthly relative risk (Death counts in a particular month divided by monthly average counts); Seasonality Index	**Peak in dry and cold season** (Jan/Feb)
	Panama	9°N/80°W	A_f/A_m	1971-1973			**Peak in middle and at end of the rainy season** (Oct-Dec)
	Paraguay	23°S/50°W	A_w	1971-1973			**Peak at end of rainy season** (Jun/Jul)
	Ecuador	1°N/78°W	A_f/B_w	1964-1966			**Moderate seasonal variation** with peak from Jan-Mar (rainy season)
	Venezuela	8°N/65°W	$A_f/A_m/A_s$	1971-1973			**No seasonal fluctuations**
	Bolivia	17°S/65°W	A_w/A_m	1944-1945			**Moderate peak at beginning of rainy and warm season** (Nov-Jan)
	Colombia	4°N/74°W	$A_f/A_m/A_s$	1968-1969			**Moderate peak in rainy season** (Jan-Jul)
	India	21°N/78°E	A/B/C	1969-1971			**Moderate peak in rainy season** (Aug/Sep)
	Sri Lanka	7°N/80°E	A_f/A_w	1964-1966			**No seasonal fluctuations**
	Malaysia	2°N/112°E	A_f	1974/1974			**No seasonal fluctuations**
	Philippines	14°N/121°E	A_m/A_f	1972-1974			**Peak in rainy and warm** (Aug-Oct) **and dry/cold season** (Jan)
	Singapore	1°N/103°E	A_f	1974-1976			**Peak in May/Jun (no seasonal climate)**
	Thailand	15°N/101°E	$A_w/A_m/A_f$	1970-1972			**No seasonal fluctuations**

RR=Relative risk; OR= Odds Ratio; CI=confidence intervals
[a] The information on temperature and precipitation refer to yearly average values and monthly average minimum and maximum values as depicted in braces; the meteorological data was taken from "WorldClimate" (www.worldclimate.com)

2.3.2 Studies of meteorological effects on mortality

Six studies assessed meteorological effects on mortality. In these studies, temperature was the main variable of interest, with some adjusting for other meteorological parameters (e.g., humidity). A few studies used equivalent temperatures, such as the apparent temperature. The regions researched were Latin America (Brazil and Mexico) and South and Southeast Asia (Bangladesh and Thailand). Figure 2.2 reflects the spatial distribution of study areas. Unlike studies investigating seasonal effects on mortality, all the meteorological studies except for one conducted in Bangladesh were based on data from urban areas. All of these studies relied on data collected after 1990 (Table 2.3).

2.3.2.1 Meteorological effects on all-cause and cause-specific mortality

Temperature exhibited a determining effect on human mortality in the reviewed studies. Like in countries of the mid-latitudes, our selected studies revealed 'U'- or 'V'- shaped temperature-mortality curves, with increasing mortality levels at low and high temperatures. Except for infectious disease mortality in Bangladesh, an adverse effect of cold temperatures was found for all causes and categories (Table 2.3). Although heat effects were found in several regions, cold effects outweighed the heat effects in most cases. The temperature range over which an adverse cold effect was observed was usually wider than the range over which heat effects were found. Moreover, increases in mortality beyond a temperature threshold were greater for cold than for heat effects (Table 2.3).

In São Paulo and Mexico City (both type 'C' climates), cold effects on all-cause and cause-specific mortality (e.g., respiratory, cardiovascular) were observed. In addition, heat effects were observed, although they were less pronounced than cold effects (Gouveia et al. 2003; Sharovsky et al. 2004; O'Neill et al. 2005; McMichael et al. 2008). However, above the 95th percentile of mean apparent temperature, a rather large increase in mortality was observed by Bell et al. (2008). Unlike other studies on temperature effects, the findings of Bell et al. (2008) reflected a heat wave effect rather than a mere heat effect. O'Neil et al. (2005) found no heat effect in Mexico City by contrasting mortality levels at the 95th percentile increment with mortality levels at the mean apparent temperature. In contrast to the dominance of cold effects described above, in Salvador (a type 'A' climate without a dry season), no cold effect was observed (McMichael et al. 2008). McMichael et al. (2008) found an increase in mortality at low and high temperatures in Chiangmai and Bangkok. In Bangkok, heat and cold effects were equally pronounced and rather moderate compared to Chiangmai, where mortality increased 84% per 1°C decrease, one of the most adverse cold effects found within this review. In Matlab (Bangladesh), a cold effect was observed for all causes of death and age groups (except infectious diseases). Although only a heat effect was observed for cardiovascular causes and for the elderly in the upper temperature ranges, the percentage increase in mortality per 1°C increase was greater than 100% and outweighed the cold effects in quantitative terms (Hashizume et al. 2009b).

2.3.2.2 Age effects and vulnerable sub-groups

Temperature effects were particularly strong in elderly age groups (Gouveia et al. 2003; O'Neill et al. 2005; Bell et al. 2008; Hashizume et al. 2009b). Concerning infants and children, cold effects need to be distinguished from heat effects. In Bangladesh, the strongest cold effect was observed among children, with an 11.1% increase in mortality, followed by elderly groups, with a 5.3% increase, whereas in São Paulo, the risk was equally high for children and the elderly (Gouveia et al. 2003). For children, the increase in mortality was mostly pronounced for all-cause mortality, whereas cardio-respiratory mortality was largely unaffected by low temperatures (Gouveia et al. 2003; O'Neill et al. 2005). Cold-related mortality increases seemed to be relevant for young age groups, but heat-related mortality increases were less pronounced among these ages. Bell et al. (2008) found no heat wave effect among children in São Paulo or Mexico City; likewise, Hashizume et al.

(2009b) did not observe heat-related mortality increases among children. Although they were less pronounced, temperature effects were also observed among adults. Low and high temperatures were particularly associated with an increased risk of cardiovascular and respiratory mortality (Gouveia et al. 2003; O'Neill et al. 2005; Bell et al. 2008; Hashizume et al. 2009b).

Gouveia et al. (2003) found little modification of temperature effects due to socio-economic factors at an ecological level. Bell et al. (2008), however, identified effect modifications due to socio-economic status, using education at the individual level as an indicator in a case-crossover study. However, the findings from this study were rather inconsistent. The greatest increase in heat-related mortality in São Paulo was found among those with no education, but in Mexico City, the greatest increase was observed among those with the highest level of education (Bell et al. 2008). In Mexico City, women were more affected by heat-related mortality, whereas no gender differences were observed in São Paulo (Bell et al. 2008).

Table 2.3: Studies assessing short-term meteorological effects on mortality

Study	Country /Region	Geographic coordinates (Lat/Long) Elevation	Temp. [°C] Rainfall [mm] [a] Climate zone	Study period	Stratifications (causes of death, age groups,)	Study design /Methods	Results
Gouveia et al. (2003)	Brazil/ São Paulo (urban)	23°S/46°W 800m	26.1 (23.3-28.7) 2022 (107-299) C_f	1991-1994	All-causes, cardiovascular, respiratory, other causes Children (0-14 yrs.), adults (15-64 yrs.), elderly (65 yrs.), Lag 0-1, lag 0-20 Socioeconomic position	Poisson regression (Generalized additive models) **Exposure:** Temperature **Confounder**: Humidity, season, day of the week, air pollution,	**Heat effect:** Increase in all-cause mortality in children 2.6% (95%CI=1.6-3.6%), adults (1.5%; 95%CI=1.1-1.8%), and elderly (2.5%; 95%CI=2.1-2.8%); CVD mortality in elderly 2.0% (95%CI=1.6-2.5%), respiratory mortality in adults 2.1% (95%CI=1.6-3.1%) and in elderly 2.3% (95%CI=1.6-3.1%); Other cause mortality in adults 2.3% (95%CI=1.4-3.2%) and in elderly 2.9% (95%CI=1.9-4.0%) **Cold effect:** Increase in all-cause mortality in children 4.0% (95%CI=3.2-4.8%), adults 2.6% (95%CI=2.3-2.9%) and elderly 5.5% (95%CI=5.2-5.7%); CVD mortality in adults 2.6% (95%CI=2.1-3.0%), elderly 6.3% (95%CI=5.9-6.7%); Respiratory mortality in adults 4.2% (95%CI=3.4-5.1%) and elderly 6.4% (95%CI=5.7-7.0%); Other cause mortality in adults 1.6% (95%CI=0.9-2.3%) and elderly 3.0% (95%CI=2.2-3.8%) Threshold temperature: 20°C Little effects by socioeconomic position (ecological level)
Sharo-vsky et al. (2004)	Brazil/ São Paulo (urban)	23°S/46°W 800m	26.1 (23.3-28.7) 2022 (107-299) C_f	1996-1998	Myocardial infarction Lag 0-1	Time series/Poisson regression **Exposure:** Temperature, humidity **Confounder**: Season, day of the week, public holidays, influenza, pollution (SO_2)	**Heat** and **cold effect**; minimum myocardial mortality temperature at 22°C (21.6-22.6°C). Cold effect stronger than heat effect. Humidity negatively associated with mortality
Bell et al. (2008)	Brazil/ São Paulo (urban)	23°S/46°W 800m	26.1 (23.3-28.7) 2022 (107-299) C_f	1998-2002	Children and youths (0-15 yrs.), adults (16-64 yrs.), elderly (≥65 yrs.) Education (None, primary, secondary, university degree) , gender Lag 0-3 (single day lag), lag 0-6 (cumulative day lag)	Case-crossover design/ Logistic regression (percentage increase in risk of mortality at the 95th percentile of mean AT compared with the 75th percentile) **Exposure:** Apparent temperature (AT) (assessment of heat effects) **Confounder:** O_3 and PM_{10}	**Heat effect**: Percentage increase in risk 4.4% (95%CI= 2.36-6.54%) for all-cause mortality, 3.3% (95%CI= -0.1-6.7%) for CVD mortality, 12.2% (95%CI= 3.1-22.4%) for respiratory mortality; Mortality in adults increased for 3.3 (95%CI= -0.1-6.8%) and in elderly for 6.51 (95%CI= 3.6-9.5%). Strongest risk observed for those with no education with 7.45% (95%CI= 0.8-14.6%); No heat effect for children
	Mexico/ Mexico City (urban)	19°N /99°W 2240m	17.2 (12.8-21.2) 634 (5-129) C_w				**Heat effect**: Percentage increase in risk 1.3% (95%CI= -0.4-2.9%) for all-cause mortality, 2.1% (95%CI= -1.2-5.4%) for CVD mortality. Mortality in elderly increased for 3.2 (95%CI= 0.9-5.6%); Strongest risk increase was observed for those with highest level of education with 5.5% (95%CI= -0.8-12.2%); No heat effect for children

CVD=cardiovascular disease; RE=respiratory diseases; CI=Confidence intervals; PM_{10}=particulate matter less than 10µm in aerodynamic diameter
[a] The information on temperature and precipitation refer to yearly average values and monthly average minimum and maximum values as depicted in braces [Yearly average value (Monthly average minimum value - Monthly average maximum value)]; the meteorological data was taken from "WorldClimate" (www.worldclimate.com).

Table 2.3: Studies assessing short-term meteorological effects on mortality *(continued)*

Study	Country /Region	Geographic coordinates (Lat/Long) Elevation	Temp. [°C] Rainfall [mm] [1)] Climate zone	Study period	Stratifications (causes of death, age groups,)	Study design /Methods	Results
O'Neill et al. (2005)	Mexico/ Mexico City (urban)	19°N /99°W 2240m	17.2 (12.8-21.2) 634 (5-129) C_w		All-causes, cardiovascular, respiratory, other causes Children (0-14 yrs.), adults(15-65 yrs.), elderly (≥65 yrs.) Lag 0-3, lag 0-6	Poisson regression; 95th and 5th percentile increment were contrasted to mean apparent temperature increment **Exposure:** Apparent temperature **Confounder:** trend, season, day of the wee, holidays; respiratory epidemics PM_{10}, O_3	**Heat effect :** None **Cold effect:** Increase in all-cause mortality in all ages 12% (95%CI=10.5-14.5%), in elderly 11.7% (95%CI=9.0-14.5%), in adults 10.6% (95%CI=7.4-13.9%), in children 10.9% (95%CI=5.4-16.7%); CVD mortality in all ages 13.8% (95%CI=9.9-17.8%),in elderly 18.8% (95%CI=14.5-23.3%), in adults 9.3% (95%CI=2.4-16.8%); respiratory mortality in all ages 21.5% (95%CI=15.6-27.7%), elderly 9.3% (95%CI=2.6-16.4%), adults 16.5% (95%CI=4.1-30.5%); other cause mortality in all ages 7.9% (95%CI=5.5-10.4%), in elderly 8.1% (95%CI=4.5-11.8%), in adults 9.9% (95%CI=6.1-13.8%)
Mc-Micheal et al (2008)	Mexico/Mexico City (urban)	19°N /99°W 2240m	17.2 (12.8-21.2) 634 (5-129) C_w	1994-1998	All-causes, Cardio-respiratory vs. non-cardio-respiratory Lag 0-1, lag 0-13	Time series/ Poisson regression (Generalized linear models)/Hockey stick model **Exposure:** Temperature **Confounder:** Humidity, day of the week, public holidays, particulate pollution	**Heat effect**: Increase in all-cause mortality 0.8% (95%CI=0.1-1.4%) above 18°C, cardio-respiratory mortality 1.1% (95%CI=0.4-1.8%) above 16°C, non cardio-respiratory mortality 1.5% (95%CI=-0.6-3.7%) above 21°C daily mean temperature **Cold effect**: Increase in all-cause mortality 6.9% (95%CI=5.7-8.1%) below 15°C, cardio-respiratory 9.2% (95%CI=7.3-11.9%) below 15°C, non cardio-respiratory mortality 8.2% (95%CI=6.0-10.5%) below 14°C daily mean temperature
	Thailand/ Chiangmai (urban)	18°N/99°E 512m	26.3 (20.7-30.4) 1180 (7-233) A_w	1995-1997			**Heat effect**: Increase in all-cause mortality 2.4% (95%CI=-0.5-5.4%) above 28°C daily mean temperature **Cold effect**: Increase in all-cause mortality 84.3% (95%CI=48.1-129%) below 19°C, non cardio-respiratory mortality 98.8% (95%CI=56.1-153%) below 19°C daily mean temperature
	Thailand/ Bangkok (urban)	13°N/100°E 12m	28.9 (25.8-32.3) 1507 (8-344) A_w	1991-1992			**Heat effect**: Increase in all-cause mortality 5.8% (95%CI=3.5-8.1%) above 29°C, non cardio-respiratory mortality 7.5% (95%CI=-4.7-25.7%) above 22°C daily mean temperature **Cold effect**: Increase in all-cause mortality 4.1% (95%CI=1.3-7.0%) below 29°C, non cardio-respiratory mortality 4.5% (95%CI=0.9-8.2%) below 29°C daily mean temperature
	Brazil/ Salvador (urban)	12°S/38°W 800m	26.1 (23.3-28.7) 2022 (107-299) A_f	1996-1999			**Heat effect**: Increase in all-cause mortality 2.5% (95%CI=0.9-4.1%) above 23°C, cardio-respiratory mortality 14.7% (95%CI=4.7-25.7%) above 28°C, non cardio-respiratory mortality 2.6% (95%CI=0.7-4.6%) above 22°C daily mean temperature **Cold effect**: None

CVD=cardiovascular disease; RE=respiratory diseases; CI=Confidence intervals; PM_{10}=particulate matter less than 10µm in aerodynamic diameter
[a] The information on temperature and precipitation refer to yearly average values and monthly average minimum and maximum values as depicted in braces [Yearly average value (Monthly average minimum value - Monthly average maximum value)]; the meteorological data was taken from "WorldClimate" (www.worldclimate.com).

Table 2.3: Studies assessing short-term meteorological effects on mortality *(continued)*

Study	Country /Region	Geographic coordinates (Lat/Long) Elevation	Temp. [°C] Rainfall [mm] [1)] Climate zone	Study period	Stratifications (causes of death, age groups,)	Study design /Methods	Results
Mc-Micheal et al (2008)	Brazil/ São Paulo (urban)	23°S/46°W 800m	20.3 (13.9-25.3) 1458 (44-233) C_f	1991-1994			**Heat effect**: Increase in all-cause mortality 3.5% (95%CI=2.6-4.3%) above 23°C, cardio-respiratory mortality 3.3% (95%CI=2.0-4.5%) above 23°C, non cardio-respiratory mortality 1.7% (95%CI=1.2.6-2.2%) above 19°C daily mean temperature **Cold effect**: Increase in all-cause mortality 6.9% (95%CI=5.7-8.1%) below 21°C, cardio-respiratory 9.2% (95%CI=7.3-11.9%) below 15°C, non cardio-respiratory mortality 8.2% (95%CI=6.0-10.5%) below 14°C daily mean temperature
Hashi-zume et al. (2009b)	Bangladesh/ Matlab (rural)	23°N/91°E	25.6 (18.3-29.1) 1997 (8-399) A_w	1994-2002	All-causes, cardiovascular, respiratory, infectious and parasitic, other-causes perinatal Children (<15 yrs.), adults (15-64 yrs.), elderly (≥65 yrs.) Lag 0-1, lag 0-13	Time series/ Poisson regression (Generalized linear models) **Exposure:** Temperature **Confounder:** Season, year, day of the week, public holiday	**Heat effect:** Increase in cardiovascular mortality 62.9% (95%CI=23.2-115.2%), infectious mortality 83.4% (95%CI=0.2-235.8%) over whole temperature range; for elderly 108.1% (95%CI=32.3-227.1%) **Cold effect:** Increase in all-cause mortality 3.2% (95%CI=0.9-5.5%), respiratory mortality (17.5%; 95%CI=8.1-27.6%). CVD mortality 9.9% (95%CI=2.9-17.4%), perinatal mortality 29.6% (95%CI=12.9-48.7%). Mortality increase in adults 1.3% (95%CI=-2.7-5.5%), children 11.1% (95%CI=2.4-20.7%), elderly (5.3%; 95%CI=1.8-8.9%)

CVD=cardiovascular disease; RE=respiratory diseases; CI=Confidence intervals; PM_{10}=particulate matter less than 10µm in aerodynamic diameter
[a] The information on temperature and precipitation refer to yearly average values and monthly average minimum and maximum values as depicted in braces [Yearly average value (Monthly average minimum value - Monthly average maximum value)]; the meteorological data was taken from “WorldClimate” (www.worldclimate.com).

2.4 DISCUSSION

Our review revealed a rather complex pattern of varying seasonal effects. Clearly, seasonal fluctuations were shaped by factors such as location, age, subpopulation, socio-economic status and, in particular, weather and climate. Moreover, patterns of decreasing seasonality over time as well as patterns of re-emerging seasonality were observed. Likewise, temperature effects differed between different regions and subpopulations. Before discussing general findings, the causes and drivers affecting and modifying mortality fluctuations shall be demonstrated. Several pathways and chains of effects potentially leading to short- and long-term fluctuations are highlighted. Overall, drivers of seasonal- or meteorology-driven fluctuations can be classified as biomedical, pathogen-specific, or socio-behavioural factors (Basu and Samet 2002; Rau 2006).

Biomedical drivers affect physiological reactions triggered by thermal conditions. Exposure to low temperatures can lead to changes in humoral activity (non-specific immune response) characterised by reduced phagocyte activity, thus hampering the host's ability to destroy viruses and bacteria (The Eurowinter Group 1997; Keatinge et al. 2000). Moreover, cold might provoke a physiological reaction of the respiratory tract, for example through bronchoconstriction, leading to an increased risk of pulmonary infections. The presence of inflammatory cells in sputum after breathing cold air indicates that cold air induces inflammatory changes in the airways (Bull 1980; Berk et al. 1987; The Eurowinter Group 2000). In addition, both cold and heat exposure can cause changes in blood chemistry. Increased plasma and blood viscosity, elevated red blood cell counts, and increased levels of several proteins are all associated with low and high temperatures (Kilbourne et al. 1982; Keatinge et al. 1984; Keatinge et al. 1986; Keatinge et al. 1989; Schneider et al. 2008). Induced haemoconcentration can result in arterial thrombosis or other cold-induced cardiovascular reflexes, resulting in cardiovascular-related death (Keatinge et al. 1984; Keatinge et al. 1986; Neild et al. 1994). Cold can further lead to vasoconstriction, whereas heat induces vasodilation; both mechanisms can strain the cardiovascular system, leading to its failure (ibid).

Pathogen-specific drivers affect the survival and replication of agents that provoke disease in the host. Different agents favour different meteorological and hydrological conditions. High temperatures generally promote the growth of bacteria. However, several pathogens, such as shigella and rotavirus, favour moderate temperatures (Hossain et al. 1990; Levy et al. 2008; Hashizume et al. 2009b). High humidity can favour the survival of pathogens in droplets (Rau 2006). Additionally, hydrological factors such as stagnant water, the lack of dilution, contamination or the breakdown of water systems associated with no, high or ongoing rainfall determine the spread of water-borne pathogens (Zhang et al. 2007a; Hashizume et al. 2009b).

In addition, socio-behavioural drivers need to be considered in order to understand atmospheric effects on human health. The importance of such factors is strikingly demonstrated by the so-called “seasonality paradox”. The “seasonality paradox” describes the phenomenon whereby countries or regions with relatively cold winter temperatures (e.g., Sweden, Canada, and Siberia) experience consistently lower excess winter mortality than countries with warm or moderate climates (e.g., Portugal or the UK). Better adjustment and social adaptation to the cold in countries with cold winters are thought to cause diminished winter excess mortality. There is evidence that, even with the same outdoor temperatures, people living in cooler climates wear warmer clothes and protect themselves better against the cold (The Eurowinter Group 1997; Donaldson et al. 1998b; Keatinge et al. 2000). Moreover, seasonal variations in socio-economic status (e.g., harvest vs. planting season) or socio-cultural practices (e.g., fasting periods) might cause seasonal differences in mortality.

Considering these different drivers and chains of effects, we aimed to explain and interpret findings from the studies included in this review. Most studies reported increased mortality during the rainy season. Generally, regions and strata (e.g., Gambia, Senegal, Nigeria, India, Costa Rica, Barbados, Dominica, Jamaica, Trinidad and Tobago, Panama, Paraguay, Ecuador, Colombia) with a high burden of infectious diseases (such as diarrhoea or malaria) and infectious disease mortality exhibited mortality peaks during the rainy season (Becker and Sadar 1981; Brewster and Greenwood 1993; Madrigal 1994; Jaffar et al. 1997; Etard et al. 2004). Subpopulations (e.g., infants and children) that suffered from a high burden of infectious disease exhibited the highest levels of mortality during the rainy season. (Becker 1981; Becker and Weng 1998; Kynast-Wolf et al. 2006; Becher et al. 2008). The aetiology of infectious diseases is quite complex, and several explanations for excess mortality during the rainy season have been brought forward. Among the most common are approaches relating to sanitary conditions and hygiene. High amounts of rainfall usually overstrain water supply and sewage systems. Moreover, stagnant water at the beginning or end of the rainy season offers good breading grounds for several disease agents. If the rainy season coincides with the hot season, elevated temperatures might furthermore enhance the replication and survival of disease agents. Additionally, the rainy season often coincides with the time of least food supply and a poor nutritional status of the population.

Whereas the mortality peak during the rainy season is well explained by pathogen-specific causes in areas or sub-groups with a high burden of infectious and particularly diarrhoeal diseases, biomedical mechanisms might provide a good explanation for the seasonal patterns exhibiting excess mortality during the dry season (e.g., Burkina Faso, Bangladesh, Brazil, Mexico, Kenya). In Bangladesh, Brazil, Mexico and Kenya, the dry season coincided with the cold season, and the excess mortality was likely cold-related. Winter excess mortality is not necessarily due to absolute low temperatures but rather due to a relative drop in temperature. In addition to biomedical reasons, social factors such as increased time spent inside and the consequently increased risks from overcrowding, poor ventilation, and indoor air pollution are likely to contribute to a winter mortality peak. In Burkina Faso, mortality exhibited a summer peak that might result from the very high ambient temperatures prevailing in that region (type B climate). Another interesting observation made in Burkina Faso was the age dependency of malaria seasonality. Although malaria generally peaked during the rainy season, among the elderly the highest rates of malaria mortality were found during the dry season. Although the vector that transmits malaria must be more prevalent during the rainy season, it seems that the elderly are at a higher risk of dying from malaria during the dry season. Poor health conditions due to heat may make the elderly more susceptible.

First and foremost, the relevance of cold effects was demonstrated in studies conducted on meteorological (temperature) effects on mortality. The temperature range over which an increase in mortality with decreasing temperatures occurred exceeded the range over which mortality increased with increasing temperatures (Gouveia et al. 2003; Sharovsky et al. 2004; Hashizume et al. 2009b). The average socio-economic status in the study regions was moderately high, and the burden of infectious disease was low (even in Bangladesh the infectious disease prevalence was low due to interventions and improved primary health care). Like winter excess mortality, cold-related short-term increases in mortality are likely to be due to biomedical reasons. In regions and strata with an increased prevalence of infectious diseases, the temperature-mortality relationship is likely to present itself quite differently.

Despite the dominance of cold effects, heat effects were found in several studies. The threshold temperatures, above which a reversion in the temperature-mortality relationship occurred, were consistently at the upper end of the temperature range, thus indicating the generally adequate adaptation of populations to high temperatures. Nevertheless, most of the studies reported heat effects on mortality. A particularly strong heat effect was observed in Bangladesh (Hashizume et al. 2009b). Moreover, the findings by Bell et al. (2008) demonstrated the relevance of very high (apparent) temperatures, so-called extreme events or heat waves. The authors used a case-crossover approach, a study design that thus far has hardly been used in this context. In São Paulo and Mexico City, pronounced "heat wave effects[8]" were observed. Such extreme temperatures might cause tremendous excess mortality, as observed for instance during the 2003 summer heat wave in Europe (Schär and Jendritzky 2004; Robine et al. 2007). Nevertheless, the empirical basis for heat wave events in the tropics is quite restricted due to data limitations.

From our review, few findings on the temporal dynamics of the atmospheric-health relationship have been reported. In Gambia, the decreasing seasonality was accompanied by decreasing mortality rates (Rayco-Solon et al. 2004). Delaunay et al. (2001) found a decrease in seasonality between the 1960s and the 1980s, but in the 1990s, seasonality increased again. The authors ascribed this pattern to the re-emergence of malaria. Despite a decrease in mortality, no relevant de-seasonalisation was found in Bangladesh. Likewise, evidence from western countries reflects conflicting outcomes. A declining magnitude of seasonality was observed in the Netherlands, the UK, Canada, and the US compared to earlier decades of the 20th century (Sakamoto-Momiyama 1978; Hare et al. 1981; McDowall 1981; Kunst et al. 1990). Nevertheless, Rau (2006) found an increase in seasonal variations in the United States. The author attributes this mainly to a decline in summer mortality due to improved air conditioning. However, Robine (2008) argued that the increase in seasonality can be explained by a growing susceptibility of populations. Modern populations are less selected; as a consequence, causes of death are less obvious, and individuals may be more sensitive to minor events.

Bearing this in mind, seasonal and meteorological effects may continue to play an important role in the future. Here we will discuss several factors and dynamics that might be particularly relevant for the effects of atmospheric conditions on mortality. Although they are still faced with a high burden of infectious diseases, developing

[8] A "heat wave effect" refers to excess mortality occurring at extreme temperatures (greater than a percentile), whereas a heat effect refers to a general increase in mortality above a threshold temperature.

countries are experiencing a rising prevalence of cardiovascular and other non-communicable diseases. Projections of mortality from 2002 to 2030 show that non-communicable mortality will continue to increase (Murray and Lopez 1997; Mathers and Loncar 2006). Moreover, in many developing countries, the number of persons aged 65 years and older is expected to increase drastically within the coming decades (Cohen 2003; Smith and Mensah 2003; United Nations 2004). The increasing average age of populations and the increasing burden of non-communicable diseases suggest not only a growing relevance of (relatively) low winter temperatures and winter excess mortality but also summer excess mortality and heat effects. In addition, future populations are likely to be exposed to higher temperatures due to climate change. Ongoing urbanisation processes occurring with changes in the mesoclimate (urban heat islands) are likely to increase exposure to elevated temperatures and heat.

2.5 CONCLUSIONS

Seasonal and meteorological effects on human mortality are highly complex and underlie modifications by non-atmospheric factors. The systematic analysis conducted within this review suggests that high amounts of rainfall and increasing temperatures are causing excess infectious disease mortality and are therefore relevant in regions and populations where such diseases are prevalent. On the contrary, moderately low temperatures and very high temperatures are adversely affecting cardio-respiratory mortality. Because of demographic and other socio-economic changes (e.g., increased life expectancy and higher burden of non-communicable diseases), both winter excess mortality and excess mortality due to extreme events are likely to gain importance. Finally, we strongly recommend intensified research on heat-related mortality in the tropics, as future temperatures are likely to increase due to climate change and urbanisation processes (urban heat islands).

CHAPTER 3: HUMAN BIOCLIMATE AND THERMAL STRESS IN THE MEGACITY OF DHAKA, BANGLADESH – A CLIMATOLOGICAL APPROACH TO HEALTH RELEVANCE ASSESSMENT

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ABSTRACT

Climate and weather conditions have profound impacts on human health and well-being. Numerous studies have been conducted to assess the relationship between atmospheric conditions and health outcomes, most of them in mid-latitude regions. Fluctuations in cardio-respiratory and infectious diseases have been linked to seasonal or short-term variations and extreme events. Atmospheric conditions vary with time and space. In addition to differences on a macro scale, meso- and microclimatic differences have been observed, such as the urban heat island phenomenon. This study analysed meteorological data taken from three measuring sites in Bangladesh, one mega-urban (Dhaka) and two (semi)-rural sites (Tangail and Mymensingh). The focus lay on seasonal fluctuations in bioclimatic conditions, the incidence of extreme events and the anthropogenic modification of the regional climate. Thermophysiological temperatures surpassed measured temperatures especially during the summer and monsoon seasons, indicating the high thermal levels to which the population is exposed. While heat stress occurrence is broadly distributed from March to September, cold stress is more limited to the months of January and December. Our assessment of the bioclimate and extreme events is based on absolute and statistically derived values, with both approaches leading to different outcomes. We argue that unless indicators are checked against health outcomes it is almost impossible to draw any meaningful conclusion.

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3.1 INTRODUCTION

Human bioclimate refers to the entirety of all climatological and meteorological parameters affecting the living organism. The relevance of climate and weather9 for human health was already recognized by Hippocrates (Hippocrates 2004, reprint). Later, Alexander von Humboldt defined climate as changes of the atmosphere affecting the human organism, thus putting human bioclimatological aspects in focus (von Humboldt 1845). Since then, numerous studies have been published focusing on the atmosphere-health relationship describing seasonal variations and non-linear relationships between multiple disease (e.g., cardio-respiratory, infectious) and temperature at high and low ends (Kunst et al. 1993; Braga et al. 2001b; Basu and Samet 2002; Braga et al. 2002; Burkart and Endlicher 2009).

Apart from temperature, the thermal environment is influenced by several additional parameters such as humidity, radiation or air movement. The interplay of these parameters affects the human heat balance and triggers several physiological reactions to restore or maintain a constant core body-temperature (Verein Deutscher Ingenieure 1998; Parsons 2003). Internal heat generated by metabolism is transferred through the skin to the surrounding atmosphere by the physiological regulation system. If this heat exchange is impeded by the surrounding conditions, the core body temperature starts to rise with potential negative consequences for human health (Driscoll 1985; Robinson 2001). In contrast, if the body loses too much heat, the core body temperature drops which can result in cardiac irregularities (Cabanac and Brimmel 1987). The efficiency of heat exchange depends to a great extent on the

[9] Commonly climate refers to the weather in some location averaged over some long period of time. Following this definition, climatological influences occur on a long-term scale and meteorological influences on a short-term scale. However, the direction and magnitude of short-term meteorological influences on human health depend on climate. Therefore, a strict distinction of the terms climate/climatological and weather/meteorological is often not possible or feasible. Particularly, in the realm of bioclimatic research this definition is not adhered to rigorously (e.g., climate definition given by Humboldt). In this article the terms climate and climatological comprise short-term and long-term influences.

temperature gradient between a body and its environment; nevertheless, as already mentioned, it is also influenced by other parameters. Humidity, for instance, affects the latent10 energy flux, and short wave radiation increases sensible heat, while air movement affects sensible and latent energy fluxes (Verein Deutscher Ingenieure 1998; Parsons 2003). In view of the complex nature of these various interactions, many have pointed to the necessity of taking a modeling approach to this matter instead of considering the diverse parameters separately. A variety of models relating atmospheric conditions to human heat sensation have been developed (Büttner 1938; Parsons 2003). In considering the overall heat balance of the human body, many of these models require meteorological information in addition to non-meteorological parameters concerning patient fitness and level of activity, clothing type and physiological adaptation to a particular environment (Staiger et al. 1997; Parsons 2003).

Apart from the general impact of atmospheric conditions, periods of extreme cold or heat can cause excess morbidity and mortality. These extreme events, usually referred to as cold or heat waves, can be assessed climatologically or epidemiologically. A climatological definition would imply the exceedance of a certain threshold value, while an epidemiological definition would imply the occurrence of excess mortality or morbidity. Despite extensive research on this topic during recent years, a clear definition for heat or cold waves does not exist (Robinson 2001; Meehl and Tebaldi 2004). From a public health perspective, the focus of any such definition should lie on the impact on human health. Nevertheless, when assessing and forecasting the effect of weather or climate on public health, modelled or statistical values often constitute the only possible approaches. Representative parameters predicting the atmospheric impact are helpful for setting up early warning systems and preparing the population with adequate measures.

[10] Energy released or absorbed by change of the aggregate state of water.

Thermal conditions vary not only with season and weather conditions but space. In addition to large scale differences resulting from geographical location, the modification of the meso- and microclimates are relevant. One widely observed mesoclimatic modification is the so-called urban climate, also referred to as urban heat island (UHI). Urban agglomerations generally exhibit higher temperatures than their surrounding areas, as the urban building structure profoundly affects short and long-wave radiation fluxes, heat storage and the water balance (Oke 1973). Most studies on urban climate are conducted in mid-latitude regions and the knowledge derived is of only limited relevance to tropical urban areas due to differences in the prevailing climatological and hydrological conditions and the urban building structure. So far, the limited number of studies conducted in tropical climates generally allows us to state that the intensity of the urban heat island in tropical regions is lower and seasonal urban-rural differences are higher during the dry season (Roth 2007).

While the human bioclimate and thermal environment has been assessed on almost every scale for countries and regions in the mid-latitudes, little is known about tropical climates. However, understanding climatic conditions and their effect on human health in these latitudes can be a key factor in developing mitigating strategies. Climate adaptive architecture and urban planning, behavioral-adjustment or public health strategies represent just a few approaches to responding to atmospheric influences. Our study aims to describe the climate and human bioclimate in Bangladesh with especial focus on the urban anthropogenic modification of the mesoclimate in the megacity of Dhaka.

3.2 DATA AND METHODS

3.2.1 Data

Meteorological data was collected from the Bangladesh Meteorological Department (BMD). This data comprises three hourly values of temperature, humidity, radiation, cloud coverage, wind speed and precipitation for three stations in Dhaka, Tangail and Mymensingh. The data was collected over a period of 10 years from 1998 to 2007. Measurements were recorded manually every three hours at 0, 3, 6, 9, 12, 15, 18 and 21 GMT and sent to the BMD headquarters where it was organized in a database and subjected to several quality and plausibility controls. Daily values were calculated for complete daily data sets and monthly values were calculated if at least two thirds of the monthly data was available (approximately 10% of the data were missing). Thermophysiological indices (TPIs) were calculated on the basis of the three hourly values from which the mean, maximum and minimum values were determined. We acknowledge that in the case of minimum and maximum TPIs, the value thus produced does not necessarily comply with the highest or lowest values occurring on that day. Data analysis was conducted using R (Version 2.10.1).

3.2.2 Thermophysiological models and indices

TPIs are output parameters of thermo-physiological models. The complexity of these models and number of parameters considered varies. The following section provides a short introduction to the models and indices used in this study. The Heat Index (HI) developed by Steadman (named apparent temperature) and modified by the US National Weather Service combines air temperature and humidity (Steadman 1979; Robinson 2001). The HI is a parameter assessing heat sensation and is defined for temperatures and humidity above 26.7°C and 40%. For cold stress assessment, the Windchill Index (WCI), also based on a model developed by Steadman, is usually applied and is defined for temperatures below 10°C and wind speeds above 4.8 km/h (Steadman 1971). These two indices were used as under hot conditions, humidity increases heat sensation whereas under cold conditions air movement increases cold sensation (Steadman 1971; Steadman 1979). In the case of both indices a reference environment with constant humidity (50% relative humidity) or wind speed (1.34 m/s) is defined which would result in the same energy gain as the actual environment. For the purposes of this study, we calculated HI whenever the thresholds were surpassed; WCI was calculated whenever temperatures fell below and wind speed exceeded defined thresholds. In-between the measured air temperature remained.

The physiological equivalent temperature (PET) (Höppe 1999) is based on the Munich Energy-balance Model for Individuals (MEMI). PET is defined as the air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed. In this way, PET allows us to compare the integral effects of complex thermal conditions outside with the experience indoors (Höppe 1999). PET requires the input parameters temperature, humidity, radiation temperature and wind speed, whereby the radiation temperature is modeled as a function of cloud coverage and temperature.

The universal thermal climate index (UTCI) was developed within the frame of the COST action 730 (www.utci.org) established by the International Society of Biometeorology (ISB). The index is based on the Fiala model, a thermo-physiological model which has been extensively validated by experimental data from numerous groups (Jendritzky et al. 2007). The index claims to be applicable for all environments, conditions and regions. The model incorporates two interacting systems of thermoregulation: the controlling, active system and the controlled passive system. The passive system is a multi-segmental, multi-layered representation of the human body with spatial subdivisions including a detailed representation of the anatomic, thermophysical and thermo-physiological properties of the human body. The model accounts for the heat transfers occurring inside the human body (blood circulation, metabolic heat generation, -conduction and -accumulation) and at its surface (free and forced surface convection, long- and shortwave radiation, skin moisture evaporation, diffusion and accumulation) (Fiala et al. 1999). The active system simulates the different responses of the human thermoregulatory system to thermal conditions, i.e. the suppression (vasoconstriction) and elevation (vasodilation) of the cutaneous blood flow, sweat moisture excretion and changes in metabolic heat production by shivering and thermogenesis (Fiala et al. 1999; Fiala et al. 2001). Like other indices, UTCI follows the concept of an equivalent temperature. A reference environment with 50% relative humidity, still air and radiant temperature equaling air temperature is defined.

3.2.3 Extreme heat and cold stress assessment

There is evidence that events of extreme heat or cold can result in an excessive adverse impact on the human body (Huynen et al. 2001; Robinson 2001; Meehl and Tebaldi 2004). In order to assess heat and cold waves, we adopted a statistical approach which defines an extreme event as the exceedance of a statistically derived threshold. Maximum temperatures provide a good measure of extremely hot or cold days, whereas the use of minimum temperatures seems to be important in assessing conditions under which there is little relief for persons during night-time (Medina-Ramón et al. 2006). For our analysis, days with heat stress were defined as those days on which the maximum temperature surpassed the 95^{th} percentile, whereas nights with heat stress were defined as nights during which the minimum temperature exceeded the 95^{th} percentile. Reciprocal maximum and minimum temperatures falling below the 5th percentile were defined as days with cold stress or nights with cold stress respectively. As there is evidence that mortality is more likely during or after the second hot night, when the interior of a building is more likely to reflect the outdoor apparent temperature (Kalkstein and Smoyer 1993) and when there is no intermittent relief, a duration criterion was integrated in the definition of a heat wave. We determined the frequency of heat and cold stress during day- and night-times for a particular day of the year. Furthermore, we determined the probability of heat and cold waves in a particular month. In order to account for the different lengths of heat and cold waves, the concept of heat and cold wave days was introduced. A heat or cold wave day refers to a 24-hour period (gliding intervals) which is part of a 48-hour period of ongoing heat or cold over which the threshold values are permanently exceeded. In order to determine the probability of a 24-hour period being a heat or cold wave day, we divided the number of days that were part of a heat or cold wave by the number of possible days[11].

3.2.4 Urban heat island assessment

The UHI was assessed by calculating the differences in monthly average values of the mean, maximum and minimum temperatures and the three TPIs between Dhaka and two reference stations located in Tangail and Mymensingh. Tangail and Mymensingh are two small towns in close proximity to the megacity area, which differ considerably in their building density and structure compared to Dhaka. Dhaka constitutes a classical urban site while the stations in Tangail and Mymensigh serve as reference stations with rural characteristics. The site in Mymensingh is situated in an agricultural environment surrounded by fields and water. The Tangail site constitutes a more built up environment than Mymensingh and might be considered as semi-rural. The difference in temperature or indices served as an indicator for the UHI and is displayed in its seasonal distribution. Before determining the differences between stations, we matched the data sets in such a way that measurement values for both sites were concurrent. Monthly differences were displayed for the mean, maximum and minimum values. Monthly differences in three-houly values were displayed as isopleths.

3.3 RESULTS

3.3.1 Seasonal bioclimate of Bangaladesh

Generally, three seasons can be distinguished in Bangladesh. The cold season, from November to March, the hot and humid pre-monsoon season (summer), from March

[11] For example: three heat waves were observed in May over the 10-year data period with the following duration time: a) 2 days (48 hours), b) 4 days (96 hours) and c) 3½ days (60 hours). The number of occurring heat wave days was divided by the number of possible heat wave days: (2+4+3 ½) / 310.

to May, and the monsoon season with heavy rainfall from May to October (also referred to as rainy season). About 90% of precipitation fell in the period May to October, while the rest of the year was relatively dry.

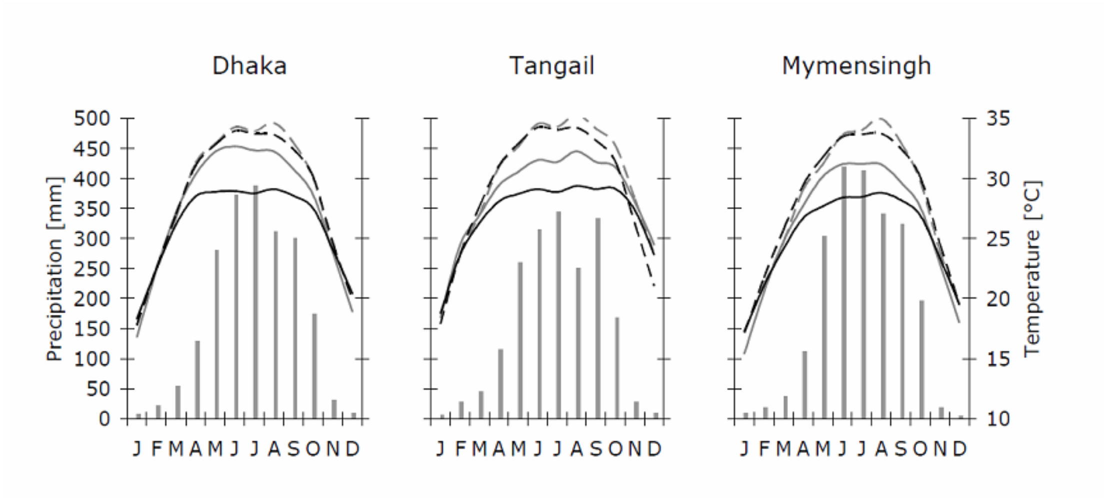

Figure 3.1: Annual variations of monthly mean temperature (black solid line), mean HIWCI (grey dashed line), mean PET (grey solid line) and mean UTCI (black dashed line), and precipitation (grey bars) in Dhaka, Tangail, and Mymensingh

The lowest values for all parameters were recorded in December and January. Average mean temperatures were almost equally high from April to September. The HIWCI peaked in August, while PET and UTCI reached maximum values from June to August. During the warm season, TPIs surpassed the temperature values (Figure 3.1). The HIWCI and the UTCI run almost parallel for all three measuring sites. According to the assessment scale of UTCI, no thermal stress occurs between 9 and 26°C. The average mean temperatures of UTCI exceeded this value in March and did not fall below 26°C (UTCI) before October. Considering average maximum temperatures, the threshold is surpassed from February to November, whereas the values for the average mean or minimum temperatures never fell below the lower threshold value of 9°C (UTCI) Celsius (data not shown).

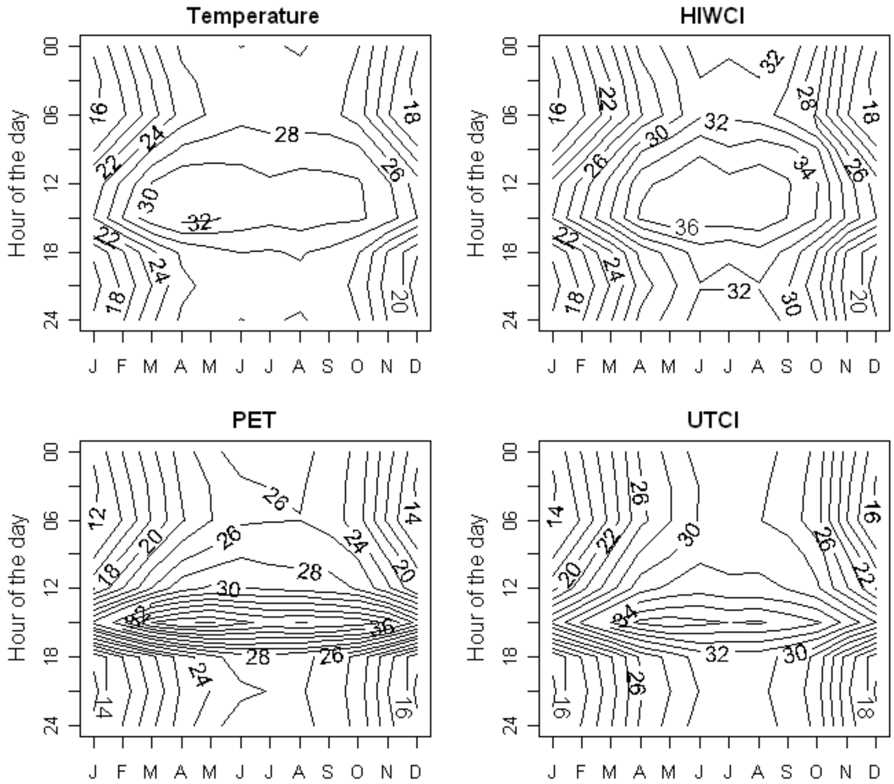

Figure 3.2: Isopleth diagrams displaying seasonal and diurnal temperature, HIWCI, PET, and UTCI distribution in Dhaka

Figure 3.2 displays temperature and TPIs as isopleths. Dhaka exhibited typical characteristics of a diurnal climate from May to September. Monthly changes were minor, while diurnal differences are pronounced. Between October and March, the isopleths followed the pattern of a seasonal climate (usually observed in the mid-latitudes). Diurnal differences were diminished and a strong gradient between months was observed. Seasonal difference in monthly average mean temperatures amounted to 10 Kelvin. A strongly pronounced diurnal gradient with quickly changing values from noon to early evening was observed for PET and UTCI.

3.3.2 Temporal occurrence and frequency of heat and cold stress in Dhaka

Figure 3.3 displays the frequency of heat and cold stress during day- and night-times at a particular day of the year. Threshold values given by the 5th and 95th percentile of minimum and maximum values are displayed in Table 3.1. Considering heat stress, most daytime temperature extremes occurred from March to July, while night-time extremes occurred from May to September, with a peak in July. The highest frequency of day- and night-time temperature extremes occurring together was observed from the mid April to the beginning of June. Extremes of HIWCI occurred from mid April to mid October, with the highest frequency being measured around June. Considering PET, daytime extremes occurred between mid-May and August, whereas night-time extremes were broadly distributed between March and October. In the case of UTCI, extremes of highest frequency during daytime can be observed from April to June, while the highest frequency during night-time can be observed between June and September. Concerning all the considered indices and temperature, cold stress is mostly limited to December and January; the highest frequency was observed in January.

Table 3.1: 5th and 95th percentile of minimum and maximum temperatures, HIWCI, PET, and UTCI

	T_{min}	T_{max}	$HIWCI_{min}$	$HIWCI_{max}$	PET_{min}	PET_{max}	UTC_{min}	$UTCI_{max}$
5th percentile	13.0	24.0	13.0	24.0	9	34.6	11.5	25.2
95th percentile	28.0	35.0	33.5	42.9	26.4	52.9	30.5	41.7

T: Temperature
HIWCI: Heat Index / Wind Chill Index
PET: Physiological Equivalent Temperature
UTCI: Universal Thermal Climate Index

Table 3.2 depicts the probability of a day (24-hour period) being embedded in a heat or cold wave. Considering temperature, the highest probability was observed in May, while the adjacent months April and June also showed an increased probability. On the contrary, regarding HIWCI, heat waves occurred between April and September with the highest probability in June. The probability of a heat wave day occurring in June is 15%. Considering PET, heat wave probability is rather low. A somewhat higher probability was observed for UTCI with the highest probability registered in June. As already observed for the frequency of cold stress days, the occurrence of cold waves is restricted between December and February. No major differences were observed between different indices, but a reduced probability was observed in terms of PET. The probability of the occurrence of a cold wave is many times higher than the probability of a heat wave.

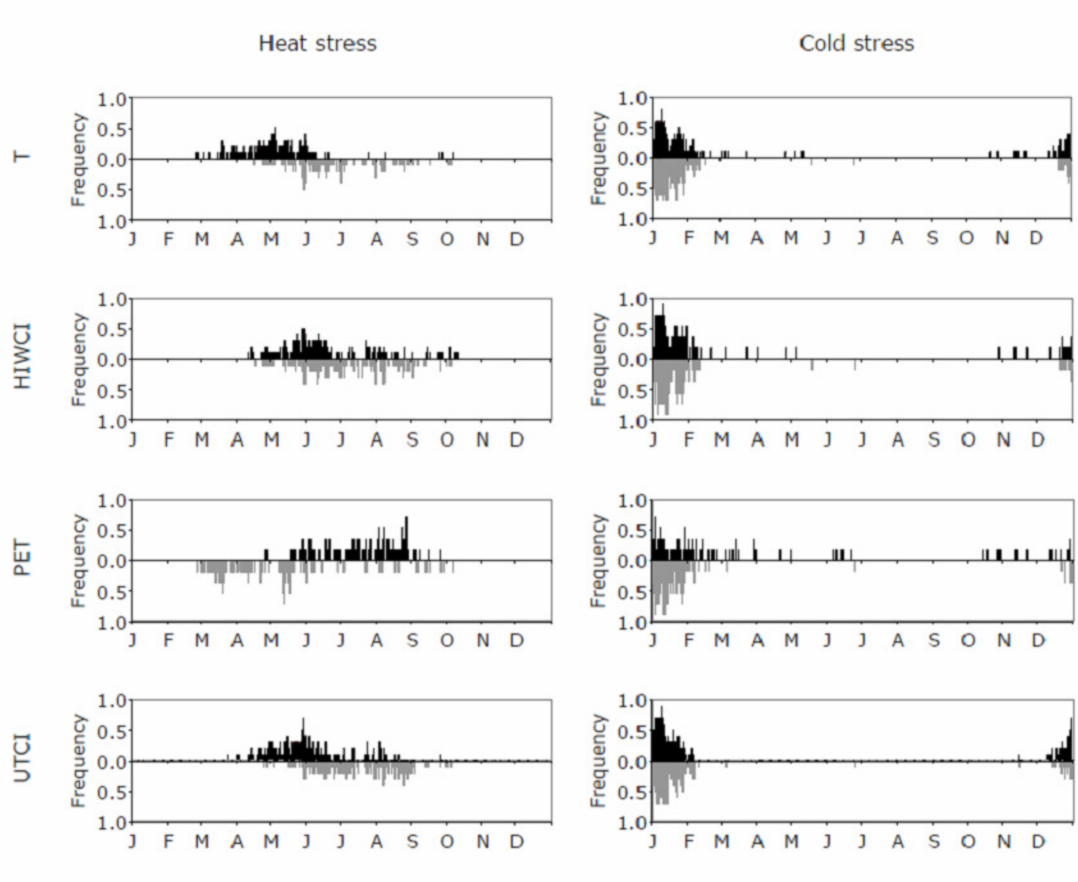

Figure 3.3: Frequency of days and nights with heat stress (left-hand column) and cold stress (right-hand columns) defined by the exceedance and undercutting of the 95th and 5th percentile of minimum and maximum temperature, HIWCI, PET, and UTCI. (Daytime frequency is displayed in the upper half of the figure and night-time frequency is displayed in the lower half of the figures)

Table 3.2: Probability of the occurrence of heat and cold wave days (periods of 24 hours) in a particular month

Month	Heat waves days				Cold waves days			
	T	HIWCI	PET	UTCI	T	HIWCI	PET	UTCI
Jan	-	-	-	-	$3.3 \cdot 10^{-1}$	$3.3 \cdot 10^{-1}$	$0.9 \cdot 10^{-1}$	$3.0 \cdot 10^{-1}$
Feb	-	-	-	-	$0.3 \cdot 10^{-1}$	$0.3 \cdot 10^{-1}$	$0.1 \cdot 10^{-1}$	$0.3 \cdot 10^{-1}$
Mar	-	-	-	-	-	-	-	-
Apr	$0.2 \cdot 10^{-1}$	$0.2 \cdot 10^{-1}$	-	-	-	-	-	-
May	$1.0 \cdot 10^{-1}$	$0.5 \cdot 10^{-1}$	-	$0.3 \cdot 10^{-1}$	-	-	-	-
Jun	$0.3 \cdot 10^{-1}$	$1.5 \cdot 10^{-1}$	-	$0.6 \cdot 10^{-1}$	-	-	-	-
Jul	-	$0.2 \cdot 10^{-1}$	-	$0.0 \cdot 10^{-1}$	-	-	-	-
Aug	-	$0.1 \cdot 10^{-1}$	$0.1 \cdot 10^{-1}$	-	-	-	-	-
Sep	$0.1 \cdot 10^{-1}$	$0.1 \cdot 10^{-1}$	-	-	-	-	-	-
Oct	-	-	-	-	-	-	-	-
Nov	-	-	-	-	-	-	-	-
Dec	-	-	-	-	$0.5 \cdot 10^{-1}$	$0.5 \cdot 10^{-1}$	$0.2 \cdot 10^{-1}$	$0.5 \cdot 10^{-1}$

T: Temperature
HIWCI: Heat Index / Wind Chill Index
PET: Physiological Equivalent Temperature
UTCI: Universal Thermal Climate Index

3.3.3 Urban heat island

Figure 3.4 and 3.5 display the seasonal distribution of differences in temperature, HIWCI, PET, and UTCI between Dhaka and the two reference sites. In both cases it can bee seen that urban-rural differences are reduced during the rainy season. During the dry season, differences between Dhaka and the reference stations ranged between one and three Kelvin, for all considered parameters. Urban-rural differences between Dhaka and Mymensingh were most pronounced during the summer season in March and April. Temporarily, monthly values in Dhaka fell below those of the reference stations. Temperature and TPI differences follow a similar seasonal distribution. The magnitude of the UHI was most strongly pronounced for minimum temperatures using Tangail as references station. Using Mymensingh as reference station, highest differences regarding HIWCI and UTCI were observed for mean and minimum values. Concerning temperature and PET, however, differences in maximum values were highest.

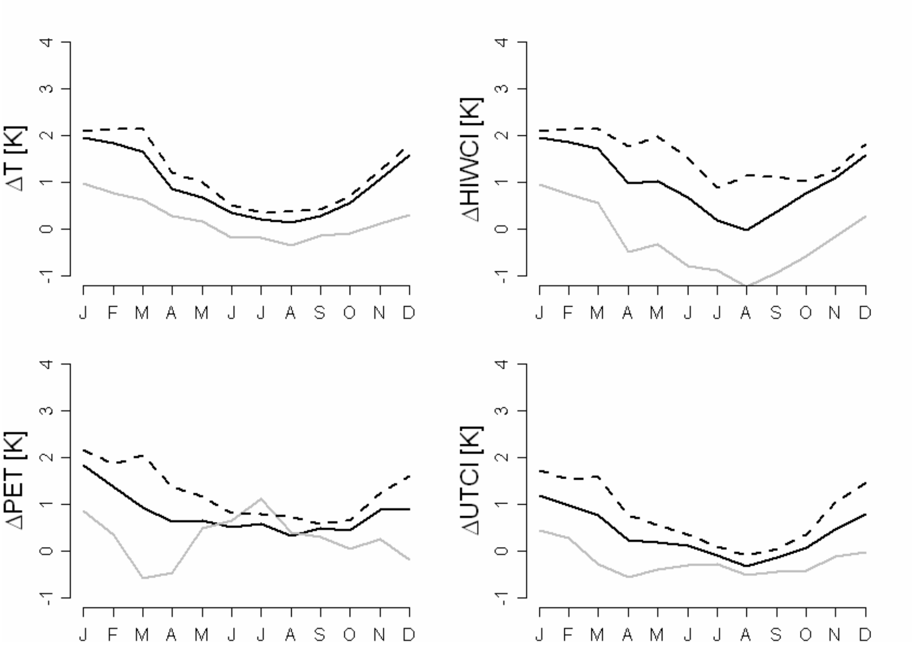

Figure 3.4: Differences in monthly mean average values (black solid line), mean maximum values (grey solid line) and mean minimum values (dashed line) of temperature, HIWCI, PET, and UTCI between Dhaka and Tangail

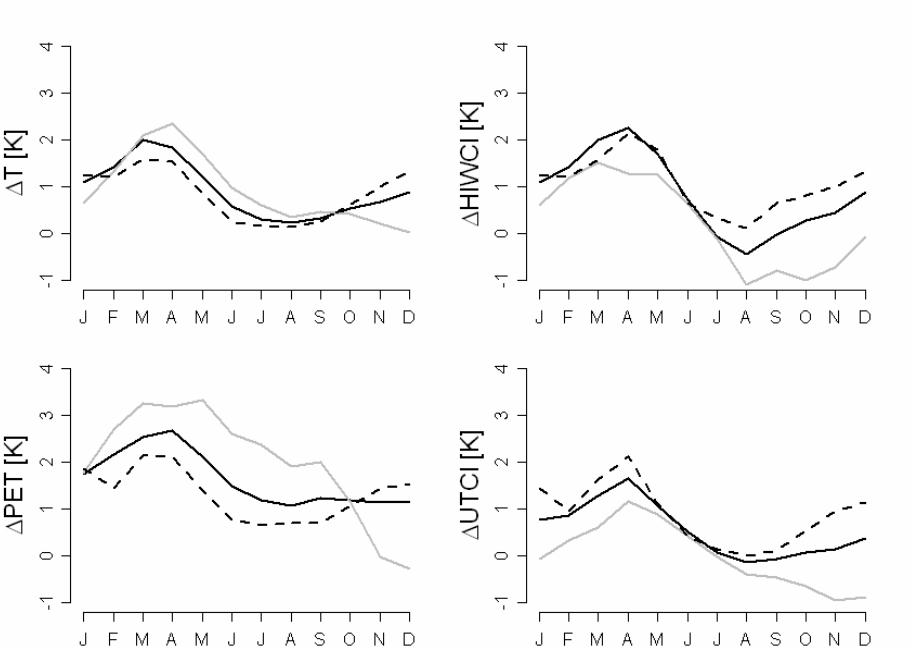

Figure 3.5: Differences in monthly mean average values (black solid line), mean maximum values (grey solid line) and mean minimum values of temperature (dashed line), HIWCI, PET, and UTCI between Dhaka and Mymensingh

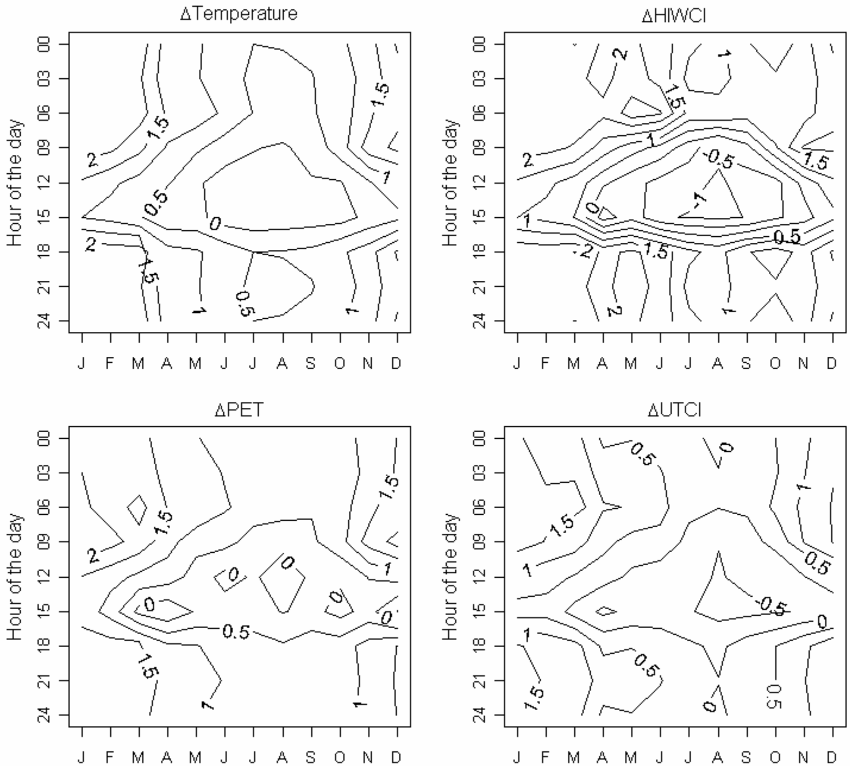

Figure 3.6: Differences in temperature, HIWCI, PET, and UTCI between Dhaka and Tangail displayed as isopleths

The seasonal and temporal distribution of the UHI magnitude is reflected in the isopleth diagrams. Differences in three-hourly values between Dhaka and Tangail are most pronounced during evening and night-times throughout the year, but particularly from October to March (Figure 3.6). Daytime Dhaka-Mymensingh differences reach their maxima around March and April. During the rainy season, differences are equally high in their diurnal distribution (Figure 3.7).

In addition to differences in temperature and TPIs, urban-rural differences were also observed for humidity, cloud coverage, mean radiation temperature and wind speed (data not shown). Humidity was higher in rural areas, particularly in Mymensingh (approximately 10% relative humidity). Mean radiation temperature was higher in Dhaka, as was cloud coverage, particularly during winter. Wind speed was higher in Dhaka compared to Tangail but lower compared to Mymensingh.

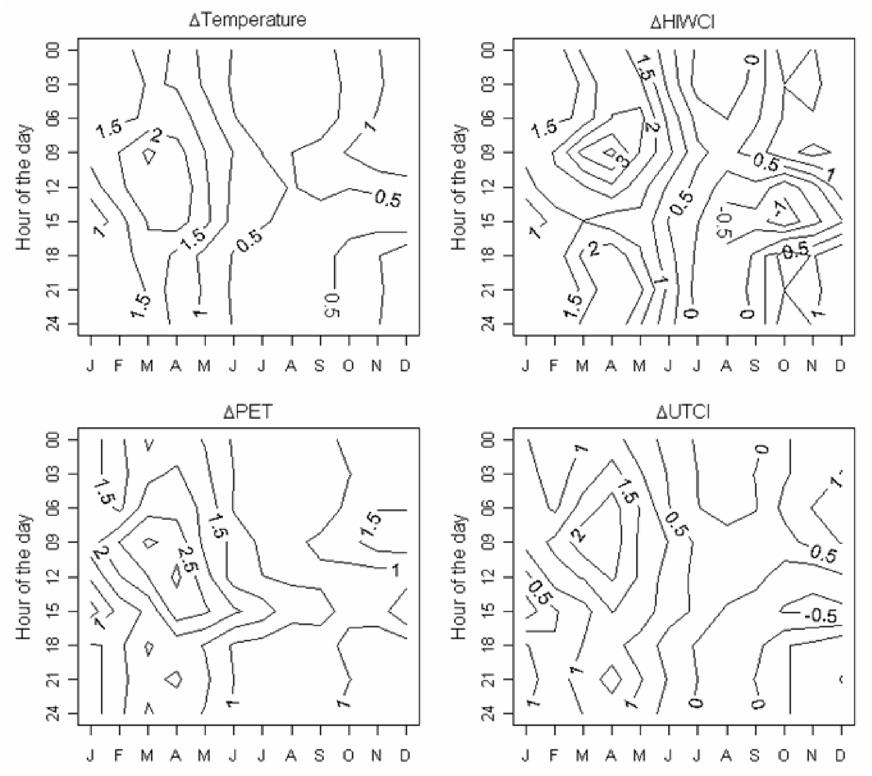

Figure 3.7: Differences in temperature, HIWCI, PET, and UTCI between Dhaka and Mymensingh displayed as isopleths

3.4 DISCUSSION

Tropical regions are usually associated with high temperatures and humidity as well as small seasonal fluctuations. According to the Köppen-Geiger classification, Bangladesh's climate is categorized as tropical winter dry (A_w) (Kottek et al. 2006). Our analysis demonstrated that climatic conditions in Bangladesh are typically tropical during the monsoon season but show characteristics of a seasonal climate during winter. Cold air masses from the Asian continent cause an abrupt fall in temperatures during the Northeast monsoon. Nevertheless, the cold thresholds calculated in this study should rather be considered as moderate values in mid-latitude countries (or according to the UTCI assessment scale). The thresholds, indicating heat stress (according to the UTCI assessment) however, are surpassed most of the year.

In this context, the suitability of an absolute assessment and the information value of TPIs require further discussion. One question of importance is whether TPIs should be regarded as indicators of well-being and thermal perception rather than predictors for human morbidity or mortality. While the winter season in Bangladesh is commonly perceived as preferable compared to the hot and humid season, the winter mortality rate is characteristically higher (Becker and Weng 1998; Burkart et al. 2011b). The crucial research question is the extent to which the human heat balance is connected to human health outcomes. Apart from human thermo-physiological regulation, external parameters such as the prevalence of certain pathogens (themselves dependent on meteorological parameters) are relevant to the atmosphere-health relationship. Furthermore, biochemical reactions influenced by temperatures could be of importance. Bull (1980) argued that excess winter mortality is due to physiological changes in cellular and humoral immunity. In addition to changes in blood pressure and vasoconstriction, exposure to cold can lead to increases in blood viscosity, higher red blood cell counts, and increased levels of plasma, cholesterol, C-reactive protein, Interleukin-6 and fibrinogen, which can result in arterial thrombosis and other cold-induced cardiovascular reflexes (Keatinge et al. 1984; Neild et al. 1994; Keatinge and Donaldson 1995). There is further evidence to suggest that the adverse effects of cold on the immune system can be ascribed to stress hormones, or to the direct effects of cold on the respiratory tract, for example bronchconstriction (Millqvist et al. 1987; Ophir and Elad 1987). Such mechanisms are not considered in current thermo-physiological models. Unless TPIs are checked against measurable health outcomes no meaningful conclusions can be drawn. Considering complexity, the UTCI clearly outclasses other indices. However, a simpler index such as the HIWCI might be beneficial for application. Further research is needed on this matter in order to provide conclusive indicators for health impacts.

Although thermal levels are comparably high or moderate throughout the year, there is evidence that cold does matter in (sub)tropical regions. High mortality during the cold season was observed in studies conducted in Kuwait (Douglas et al. 1991) or Bangladesh (Becker 1981; Becker and Weng 1998; Burkart et al. 2011b). Douglas et al. (1991) argued that the adverse effects of cold are not a consequence of low absolute temperatures, but of a seasonal fall below annual mean temperatures. In addition to physiological mechanisms, social, cultural and behavioural adaptation strategies determine the impact of cold (or heat). Research conducted by the Eurowinter Group demonstrated that regions with harsh winter climates exhibit a lower level of excess winter mortality than climates with moderate winter climates (The Eurowinter Group 1997). Housing and clothing in Bangladesh are adapted to the hot weather conditions prevailing for most of the year, while adaptation to the limited time-frame of relative cold is probably insufficient. Cold stress and increased cold wave probability occur over a relatively short time-frame. In the case of heat stress, the time-frame of days and nights with heat stress is broader. Thus the probability for the occurrence of a cold wave is considerably higher than for heat waves. The highest probabilities of heat waves were determined during the summer season regarding temperature, but shifted toward the monsoon season regarding TPIs. The combination of a high prevailing humidity, low diurnal amplitudes, persisting elevated daytime thermal conditions and little night-time cooling (this is due to reduced net long-wave emission) results in persisting thermal stress during the monsoon season.

Excess temperatures, marking the UHI found for temperature and TPIs were equally high for the parameters considered. The UHI was most intense during the cold season but excess (equivalent) temperatures were still recorded throughout the summer and rainy seasons. While the urban heat island phenomenon might mitigate cold stress during the cold season, urban excess temperatures increase the thermal load during the hot and humid (pre-)monsoon season. In a climate of persistently and constant high thermal levels even small excess temperatures might serve to cause excess morbidity and mortality if a certain breakpoint is passed. Indeed, there is evidence which suggests that in rural regions, cardiovascular mortality is at its lowest during the warm and rainy seasons, whereas the same figures for urban areas exhibit (secondary) peaks during the same time (Burkart et al. 2011b). This could either be caused by urban excess temperatures or by the higher susceptibility of urban populations to heat effects. It most likely represents an interaction of both causes.

In mid-latitude regions, the UHI has often been described as a night-time phenomenon. Urban areas heat up more slowly than rural areas and show lower temperature maxima, as building materials divert and store heat into the building structure. At night, the cooling rate of urban areas is lower as the structure emits heat only gradually. These mechanisms could be responsible for the UHI differences observed between Dhaka and Tangail. However, building structures and materials in developing countries differ strongly from those used in industrialized countries. While the construction materials used in western countries usually have a high heat conductivity and specific heat capacity, this is not the case for the corrugated metals and brick types often used as building material in developing countries. In addition to the modifying effects of the building materials used, the association between sensible and latent heat could also be of particular significance in explaining characteristics of the tropical UHI. Water vapour capacity increases exponentially with temperature. Tropical air is able to contain exponentially more humidity than the air found in mid-latitude climates. Due to the high water availability in rural regions and the high atmospheric intake capacity, sensible heat flux is reduced and temperatures rise more slowly and not to the same extent as in urban areas. This could represent the cause of daytime urban excess temperatures[12]. During night-time, energy is released as water vapour condensates leading to reduced cooling (in rural areas). Mymensingh can be

[12] The energy amount needed to evaporate one gram of water, increasing relative humidity of one cubic meter air about 2-3% is up to about 7 kilojoules. The same amount of energy would increase the sensible heat of one cubic meter air about 2 Kelvin. (Evaporation enthalpy, specific heat capacity and air mass per cubic meter are temperature dependent. The calculations are based on average values for approximately 30°C.)

considered a more rural environment compared to Tangail in terms of structure of buildings. The Mymensingh measurement site is located in an agricultural area in proximity to water bodies. The relative humidity level is approximately 10% higher than in Dhaka. Tangail which is more built up than Mymensingh only showed 2 to 3% increased levels. We conclude that in reference to areas with high water availability, the UHI is a daytime phenomenon (excess temperatures higher during daytimes) as latent energy fluxes reduce daytime heating as well as night-time cooling. With decreasing water availability due to increased building structure and sealing the tropical UHI is more and more shifted towards a night-time phenomenon as observed in mid-latitudes.

The pattern of increased mean radiant temperature follows the distribution of temperature and TPIs and can probably be explained by the same mechanisms. The high cloud coverage in Dhaka, particularly during winter, is most likely to be caused by urban aerosols serving as condensation nuclei. Concerning wind speed the mechanisms seem to be more complex. Surface roughness in the urban area may reduce wind speed, but the canalization of air movement (Bernoulli effect) or thermally induced wind could serve to increase wind speeds. The open field environment with little surface roughness gives a good explanation for high wind speeds in Mymensingh. In Tangail, a more built up environment, winds might already have been slowed down. Although, surface roughness is higher in Dhaka, canalization and thermal effect might cause increased wind speeds in comparison to Tangail.

Data availability constitutes a general problem in tropical developing regions. While numerous measurement campaigns have been launched in western countries designed to assess the urban heat island, this study had to rely on secondary data from the Bangladesh Meteorological Department. This brought the advantage of a long study period in the time series (10 years). However, the measurement sites were chosen to serve synoptic purposes, meaning that they are more likely to be representative of the macro- rather than the mesoclimate.

3.5 CONCLUSIONS

Until today, only few studies have been conducted on bioclimate and the health-atmosphere relationship in tropical regions. Heat stress is commonly believed to be a major issue in the tropics and the pre-monsoon season is supposed to be a period of high thermal stress due to high maximum temperatures. In this study we discussed several climatological approaches to health relevance assessment of weather conditions. We pointed out that in addition to the summer/pre-monsoon season, other seasons require attention concerning their health risk. During the monsoon season little relief is offered during night-time and the probability of a heat wave is increased, particular concerning TPIs. Furthermore, we argued that low temperatures and cold stress need to be considered. Although temperatures and modeled temperatures (TPIs) are constantly high (according to the absolute assessment scale provided with TPIs), there is evidence that periods of relative cold constitute health threats due to inadequate adaptation in (sub)tropical counties. We followed a statistical percentile-based approach for assessing cold stress, and found that extremes are restricted to the months of December and January. The megacity of Dhaka exhibited considerable excess temperatures, particularly during winter but also during the pre-monsoon season. Although the temperature differences remain below those observed in mid-latitude regions, the UHI might be epidemiologically relevant for tropical regions due to the persisting high levels of temperature and thermo-physiological temperatures. Nevertheless, we point out the necessity of checking thermo-physiological models and statistical approaches against measurable health outcomes in order to reach reliable conclusions about their explanatory power.

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CHAPTER 4: ASSESSING THE ATMOSPHERIC IMPACT ON PUBLIC HEALTH IN THE MEGACITY OF DHAKA, BANGLADESH

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ABSTRACT

Urban areas are hot spots, contributing to climate change on multiple scales; but they are simultaneously affected by and most vulnerable to the effects of climate change due to their high density of susceptible population, their often risk-aggravating environmental conditions and low socio-economic standards (Kraas 2007; Grimm et al. 2008). The changes in climate may have a severe impact on human illness and mortality and are likely to produce a sustained change in the occurrence and spatial distribution of diseases. Although the relationship between temperature and human health has been studied for several regions and cities in the developed world, there is still little knowledge about the atmospheric influences on the burden of disease in developing countries, in particular tropical climates. However, the increase in the speed and extent of worldwide urbanisation, often referred to as 'urban turn', is leading to the emergence of so-called megacities, more than three-quarters of which are situated in the developing world. Dhaka, now the eleventh-largest city in the world and one of the world's fastest growing, is set to accumulate many of these anticipated public health problems (Roth 2007; Burkart et al. 2008).

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4.1 INTRODUCTION

4.1.1 Human health and the atmospheric environment

Climate and air pollution (atmospheric environment) have major impacts on human health and wellbeing. In particular, urban climates are believed to be hazardous. Their influence and impact, however, are complex (Wichmann et al. 2003; Moriske 2004; World Health Organisation 2005). Major aspects of climate and urban climate in particular are physical and chemical in nature, both consequences of the modified urban meso-climate, often referred to as the urban heat island effect, and the high levels of air pollution (Oke 1990; Helbig et al. 1999; World Health Organisation 2005). Concerning the physical and particularly thermal impacts, the nature and magnitude of the interdependencies between temperature and human health have been increasingly recognised (Martens 1998; Samet et al. 1998; Patz et al. 2000; Basu and Samet 2002; Medina-Ramón et al. 2006). Non-linear relationships have been observed with increased mortality at high or low temperatures (Kunst et al. 1993; Braga et al. 2001a; Braga et al. 2002). Both hyperthermia and hypothermia are generally linked to cardio-respiratory morbidity and mortality (Kunst et al. 1993; Braga et al. 2002; Schär and Jendritzky 2004). In many regions of the world a seasonal variation of morbidity can be observed. In countries of the mid-latitudes death rates in winter are generally higher than those in summer, although heat waves can cause excess mortality (McMichael 2001; Braga et al. 2002; Schär and Jendritzky 2004; Rau 2006).

Furthermore, epidemiologic studies have consistently provided evidence of adverse health effects arising from air pollution. Particulate matter and SO2 pollution are strongly implicated in acute morbidity and mortality, and an increased incidence of lung cancer and cardiovascular disease has been observed (Dockery et al. 1993; Pope et al. 2002; Wichmann et al. 2003; Brook et al. 2004; Moriske 2004). Periods of smog events are often associated with high levels of morbidity and mortality (excess mortality) (World Health Organisation 2005). However, there is also evidence that current ambient levels of PM_{10} are associated with increases in daily cardio-respiratory mortality and in total mortality (American Thoracic Society 1996) Additive and synergetic effects between different meteorological and air pollution variables are very likely. Although numerous studies have demonstrated that air pollution is consistently associated with adverse health effects (Samet et al. 2000; Wichmann et al. 2003; Bell et al. 2004; Brook et al. 2004; Moriske 2004; Dominici et al. 2006), its role is often ignored in assessing the effects of temperature variability on human health. While in most studies assessing air pollution effects temperature is usually used as a confounder, only a few recent studies consider air pollution as a confounder while assessing temperature effects (O'Neill et al. 2003; Rainham and Smoyer-Tomic 2003; Ren et al. 2006). However, air pollution may make people more vulnerable to the effects of temperature variability (Ren et al. 2006).

The heat-mortality and -morbidity relationship varies across time periods, regions and populations. Time series studies have shown that different cities and population groups exhibit different responses to heat. For instance, the relationship between heat and mortality differed for Delhi, São Paulo and London (Hajat et al. 2005), and the impact of heat waves on mortality differed by city for a study of London, Milan and Budapest (Hajat et al. 2006). Klinenberg (2002) noted that the urban poor and people with fewer social connections were most at risk of death during the Chicago heat wave of 1995. Furthermore, the risk for heat-related mortality was higher among the African-American population (Kaiser et al. 2007). Smoyer et al. (2000) showed that the strongest relationship between heat and mortality in Southern Ontario occurred in cities with relatively high levels of urbanisation and high costs of living. In Dhaka, seasonally differing hospital admissions could be observed for Dhaka Children Hospital, with higher cases of acute respiratory infections during winter (Bhattacharjee et al. 2002).

The underlying reasons for these differences are only partially understood. The demographic composition and socio-economic status of population groups might be of importance, reflecting the level of economic and technological development, pre-existing health status and the quality and availability of health care. Further, the degree of urbanisation, population density, urban design and morphology, and housing factors (e.g., higher heat stroke risk amongst people with no air conditioning and trees or other plants near their residence) could be crucial in determining the atmospheric impact (Kilbourne et al. 1982; Patz et al. 2000).

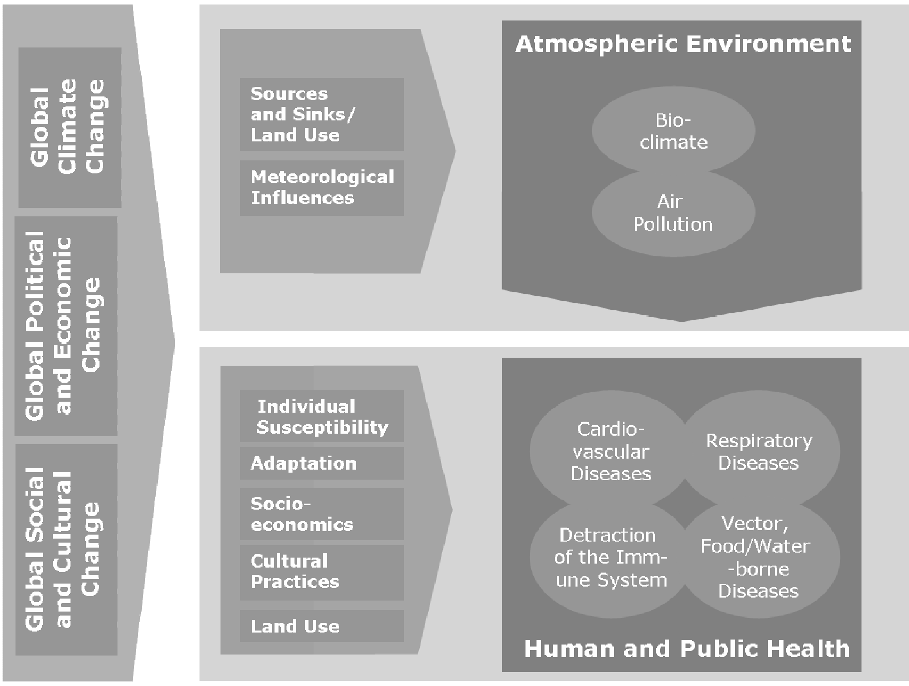

Figure 4.1: Impact of the atmospheric environment on human health and modifying influences

Acclimatisation is another crucial aspect (Figure 4.1), particularly when appraising the impacts of global climate change. Areas in which extreme levels of heat are rare display a higher level of heat-related deaths, as these populations are hypothesised to be less acclimatised to high temperature (Kalkstein 2000; Kinney et al. 2008). Past research has shown that heat waves occurring early in the summer season have a greater impact on mortality than those of similar intensity occurring later in the season (Greenberg et al. 1983; Kalkstein and Davis 1989; Kalkstein and Smoyer

1993). Hence, physical acclimatisation can refer to a seasonal timeframe or to a longer timeframe (Kinney et al. 2008).

People may adapt to changing conditions physically or socio-culturally through modification in their activities or increased use of air conditioning. Nevertheless, global change is not restricted to climate change but includes all the processes of global political, economic, social and cultural change (Figure 4.1). All these aspects have to be considered in order to appraise and evaluate the possible hazards arising from a changing climate and to make necessary interventions.

4.1.2 Research needs

The investigation of health hazards arising from a disturbed atmospheric environment in megacities as well as the hazards arising from a changing climate are an area that needs to be explored. Urban areas are especially vulnerable due to their high density of susceptible population and their often risk-aggravating environmental conditions (Kinney et al. 2008). Furthermore, the influence of the urban heat island effect may worsen the public health situation for city dwellers in particular. (Mega)cities in developing countries may be affected the worst due to their precarious socio-economic conditions and high levels of pollution. However, there is a lack of research into urban tropical climates and epidemiological aspects of temperature and weather-related diseases in the developing world, as these countries lack the adequate financial, technological and scientific means (Confalonieri et al. 2007; Roth 2007). Nevertheless, of the 20 megacities (> 10 million inhabitants) identified in 2003, 14 are located in the (sub)tropics. By 2030, Asia and Africa will each have more urban dwellers than any other major area, with Asia alone accounting for over half of the urban population of the world (Roth 2007; Burkart et al. 2008). For taking skilled interventions, it is essential to understand which diseases are affected the most by temperature and air pollution. The analysis of threshold values – above which an abrupt rise in morbidity illness and mortality can be noticed (depicting an extreme event) – is essential for appraising impacts of climate change, as well as establishing early warning systems.

4.1.3 Study area: Dhaka, capital of Bangladesh

Dhaka, the capital of Bangladesh, is the eleventh largest city in the world and one of the fastest growing (6.2% per year). The city is outstanding among Bangladeshi cities in terms of economic, social and political opportunities but nevertheless is one of the poorest cities in Asia. Dhaka accumulates many of the problems anticipated for megacities. It is confronted with a high poverty rate, socio-spatial fragmentation processes and the loss of governability. Moreover, it is facing ecological challenges like air, water, soil pollution and a heavy burden of disease (Centre for Urban Studies 2006; Burkart et al. 2008). High levels of pollution and air pollution originate from the brick-kiln industry surrounding the city, from the high traffic volume in- and outside of Dhaka as well as an immense number of open fires used for cooking and heating by the many poor of the city (Karim 1999; Begum et al. 2006; Burkart et al. 2008). A large proportion of Dhaka's population is living in so-called slums or informal settlements (unauthorised slum settlements), areas which are characterised by their extremely low and poor living standards. About 3.8 million people are living in approximately 4,900 slums distributed over Dhaka (Figure 4.2) (Centre for Urban Studies 2006). Our research is addressing those urban poor population groups.

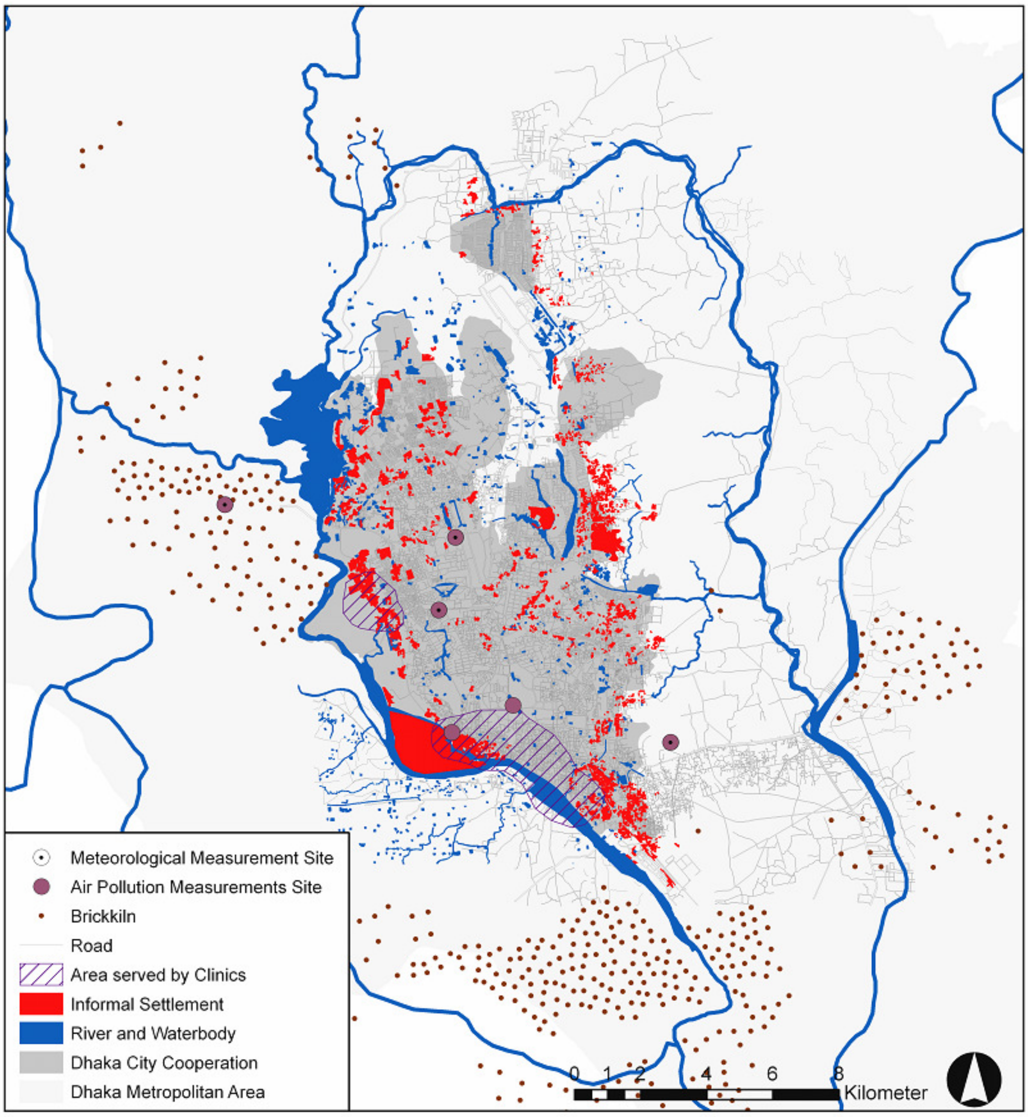

Figure 4.2: Dhaka Megacity: spatiality of health determinants and location of test and investigation sites

4.2 METHODOLOGY

4.2.1 Identifying climate-sensitive health outcomes

Focusing on the extent and magnitude of the effect of climate and air pollution, our research approach is based on an attempt to link information about atmospheric conditions, comprising meteorological variables and air pollution levels, with information about human morbidity. Besides the impacts on cardio-respiratory diseases, infectious diseases transmitted by vectors and diseases caused by pathogens replicating in water or food are also affected by climate and should therefore be a focus of research interest. Additionally, the modifications arising from air pollution are of particular interest, as well as the evaluation of the influencing factors such as socio-economic status and cultural practices. In order to approach these formulated research questions, a comprehensive data base including environmental as well as health data needed to be compiled. Collecting data is most challenging when working on developing countries, especially when working on urban poor population groups and informal settlements. Within the frame of ecological time series studies, time-varying conditions such as pollution levels or temperature are associated with time-varying event counts. Ecological studies analyse daily population-averaged health outcomes and exposure levels. Unfortunately, the aggregation of data that define ecological studies results in a loss of information that can lead to ecological bias. However, if the health effects are small and the disease outcomes are rare, the biases from ignoring the data aggregation across individuals should be small (Wakefield and Salway 2001). Another aspect that needs to be considered in time-series analysis is that temporally varying non-climatic influences, such as season, hydrological conditions or varying food prices can confound the relationship between atmospheric conditions and health outcomes. Especially season is a strong predictor of morbidity and other signals are practically buried under this factor. Adjusting for confounding factors and extracting relevant signals is of high importance when assessing the influences of the atmosphere. Factors that vary across individuals or communities but do not vary from day to day cannot confound the relationship between daily variations in atmospheric conditions or health outcomes (Peng and Dominici 2008). Also of high relevance is the consideration of the lag period which describes the time displacement after which the exposure to a certain atmospheric condition results in a health outcome.

4.2.2 Data basis

Meteorological data was received from the Bangladesh Meteorological Department (BMD). This data comprises three-hourly values of average, maximum and minimum temperature, humidity, radiation, cloud coverage, wind speed and precipitation at one measuring side in Dhaka (Figure 4.2). In addition, particulate matter was measured at six sites in Dhaka (Figure 4.2). Concerning health data, the main challenges lie in the poor habits of data compilation and storage prevalent in Bangladesh. Most data is kept in analogue form and only aggregated data is stored digitally. Daily hospital data from ten clinics associated to the Urban Primary Health Care Project (UPHCP) were collected and digitalised. These clinics treat predominantly urban poor population groups which are most likely to be vulnerable. The data dates back until July 2006, information previous to that date is not available. Daily data, regarding the number of patients as well as information about the type of disease from which a patient was suffering and further personal information about the patient, such as age and sex, were digitised.

4.3 PREVALENCE AND SEASONALITY OF ENVIRONMENTAL DISEASES IN URBAN POOR POPULATION GROUPS

4.3.1 Prevailing environmental diseases in urban poor population groups

Human and public health is determined and influenced by a multitude of factors. Besides the individual susceptibility and genetic expression, physical and social settings play major roles. Environmental conditions, diet and nutrition, as well as lifestyle and health strategies take part in determining health outcomes of individuals and populations. Nevertheless, the prevalence of pathogens as a result of geography, climate and hygiene is crucial. Figure 4.3 shows the dominance of different environmental diseases at the clinics associated to the Urban Primary Health Care Project. Primarily, it can be seen that acute respiratory infections (ARI) as well as diarrhoeal diseases add up to more than 50% of all diseases. Also the environmental burden of disease determined by the World Health Organisation states comparably high cases of both diseases (World Health Organisation 2007). Furthermore, skin, ear and dental diseases add up to almost one fifth of all diagnosed diseases, while scabies caused by *Sarcoptes scabiei* is clearly dominating. Scabies is highly contagious and prevalent in most parts of the world. Hygienic conditions determine the spread of this disease, and overcrowding promotes the diffusion of the parasite. Special forms of scabies particularly occur in chronically ill, malnourished or immunosuppressed people and are especially contagious (Robert Koch Institut 2005). Obviously, this evidence can explain the high prevalence of scabies in informal settlements and shows the current major problems in dealing with and containing the disease.

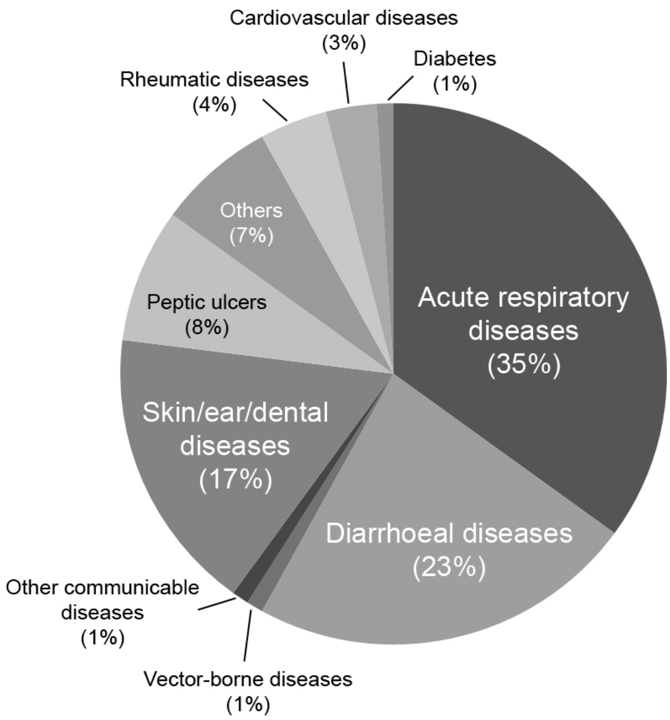

Figure 4.3: Environmental diseases occurring at the UPHCP clinics

Gastric diseases such as peptic ulcers that are caused by chronic inflammation make up 8% of the total quantity of diseases. The spiral-shaped Helicobacter pylori bacterium that lives in the acidic environment of the stomach is considered as a major causative factor of these ulcers. In the developed world as much as 80% of ulcers are associated with Helicobacter pylori. Ulcers can also be caused or worsened by drugs such as aspirin and other non-steroidal anti-inflammatory drugs (NSAIDs), and gastric acids and physical or mental stress are further considered of importance in the development of peptic ulcers (Mertz and Walsh 1991; Chiba 2004; Choung and Talley 2008). While the prevalence of Helicobacter pylori has caused ulceration declines in the Western world due to increased medical treatment, the bacterium is still of high importance as a causative factor in the developing world. Helicobacter pylori are contagious, although the exact route of transmission is not known (Cave 1996; Delport and van der Merwe 2007). Person-to-person transmission by either the oral-oral or faecal-oral route is most likely, and transmission by contaminated groundwater is also plausible (Brown 2000). Most research on peptic ulcers was conducted in the developed world; however, it is likely that the prevalence in developing countries is higher for the above-described reasons that evoke peptic ulcers. How an increase in ambient temperatures could affect the spreading of Helicobacter pylori is unclear.

Chronic diseases such as diabetes, cardiovascular or rheumatic diseases account for less than 10%. Cross sectional studies in rural areas in India and Pakistan, however, demonstrated a high prevalence of diabetes (Shera et al. 1999; Khatib et al. 2008), suggesting that the hospital admission counts do not adequately reflect the real burden of diabetes and other chronic diseases.

To analyse and interpret hospital admission data accurately, it is essential to realise that admission to hospitals and diagnosis of certain diseases is depending also on the awareness and perception of health. Whether a person feels healthy or considers his or her state of health as pathologic determines whether he or she seeks medical treatment. Likewise, practitioner awareness and knowledge about certain diseases decides whether a disease is correctly diagnosed and treated. Given these explanations one must realise that the dominance of diseases in a hospital does not necessarily represent the real burden of disease of a population group, but is also the reflection of the cognition of patients and physicians. The relatively low occurrence of chronic diseases such as diabetes, cancer, hypertension and heart disease might be due to the non-recognition of these diseases rather than the reduced occurrence. Although these diseases are often referred to as prosperity or lifestyle diseases, expressing that modern affluent living conditions are enforcing the risk of suffering from such illnesses, the prevalence of these chronic diseases might be underestimated due to the lack of awareness in urban poor population groups. The importance of health perception was also shown by a study comparing self-reported illness in Bihar to self-reported illness in Kerala and the United States. The study comes to the result that self-reported illness is lowest in Bihar, the poorest state in India, with the lowest life expectancy. Kerala, which has invested most heavily in education and has the highest literacy rate and life expectancy, and the United States have both drastically higher rates of self-reported illness (Sen 2002).

4.3.2 Seasonal distribution of environmental diseases

Seasonal fluctuations in mortality as well as morbidity are a persistent phenomenon across populations. Hippocrates stated the importance of season in his work on "Air, Waters and Places" written almost 2500 years ago (Hippocrates 2004, reprint). In Western countries of the northern hemisphere, mortality is typically higher in winter than in summer, while in tropical regions morbidity is highest during the warmer seasons (Becker 1981; Braga et al. 2002; Schär and Jendritzky 2004; Rau 2006; McMichael et al. 2008). Thereby, socio-demographic and socio-economic factors play as important a role for seasonal mortality as they do for morbidity and mortality in general. Several studies show that the fluctuations between seasonal mortality are smaller the higher the socio-economic standard or the education level (Klinenberg 2002; Hajat et al. 2005; Hajat et al. 2006; Rau 2006).

For the investigated hospital admission data, differing temporal and spatial distributions could be observed. Divided into separate disease groups, acute respiratory diseases clearly increase during the cold season (Figure 4.4). Temperature has a determining effect on acute respiratory infectious diseases and incidence rates are typically highest during colder months. However, it is unclear to what extent the high levels of air pollution during this season are enforcing the occurrence of acute respiratory diseases. Exposure to airborne particulates leads to acute inflammation of the airways, damages of lung tissue and a detraction of the immune system (Kappos et al. 2004). In Dhaka, air pollution levels peak during the winter monsoon from the middle of December to the middle of March due to the stable atmospheric conditions and could therefore contribute to the elevated incidence rate. Figure 4.6 shows the high levels of particulate matter during the month of February compared to levels in November (post-monsoon) and April (pre-monsoon). Further, the figure demonstrates the spatial differences existing between different locations within the city. While air pollution levels at the urban fringe are rather moderate they are almost double at the inner urban traffic site. In Islambagh, a slum area with intensive plastic recycling industry, levels rise over 200 µg per m^3 in February, about double the level of November and almost three times as high as particulate matter levels measured at the urban fringe site. This demonstrates the extra burden slum dwellers and poor population groups are facing.

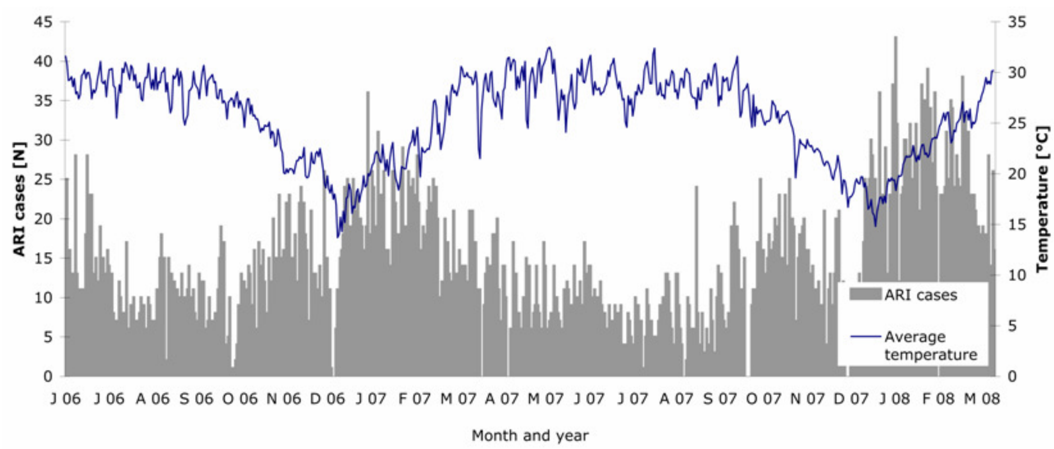

Figure 4.4: Temporal distribution of ARI cases in the UPHCP clinics between July 2006 and March 2008

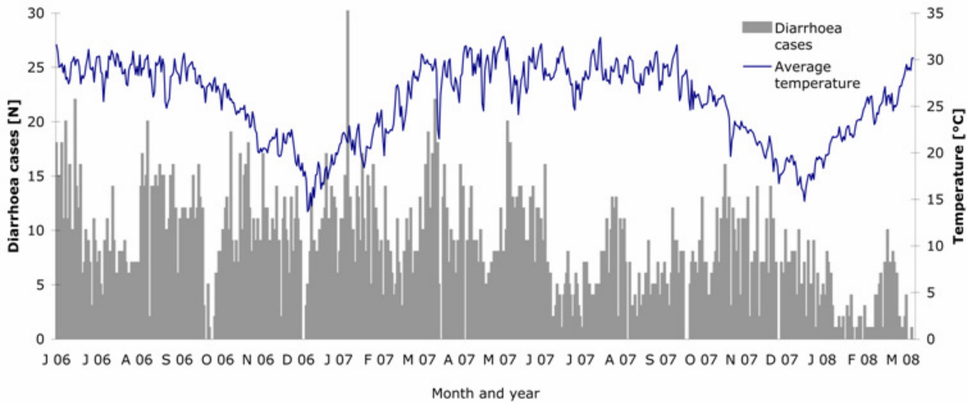

Figure 4.5: Temporal distribution of diarrhoea in the UPHCP clinics between July 2006 and March 2008

Concerning diarrhoeal disease, it could be observed that the occurrence shows temporal differences with several minima and maxima occurring over time (Figure 4.5). However, no clear pattern could be observed. In tropical regions typically a summer peak of mortality can be noted which is ascribed to the dominance of fatal diarrhoeal diseases (McMichael et al. 2008). The differing occurrence of diarrhoeal diseases observed at the clinics of the UPHCP might be due to regional or local geographical, climatological and hydrological differences. The transmission pathways of pathogens and modifying factors are complex. The infection is generally spread from person to person via oral-faeces, food and drinking water. Epidemics are frequent in overcrowded populations with poor sanitation (Zhang et al. 2007a) demonstrating the importance of socio-economic and cultural circumstances for the spread of the disease. According to Hashizume et al. (2007) causative agents of diarrhoea are also likely to be different in Dhaka compared to other regions. The observed pattern of the prevalence in Dhaka might be caused by interacting thermal and hydrological effects. While high temperatures generally promote the growth of bacteria, stagnant water during low rainfall periods and the lack of dilution of sewage systems may further cause an increase in diarrhoea cases (Hashizume et al. 2007; Zhang et al. 2007a). Various studies found an increase in diarrhoea incidence after high rainfall events suggesting that rainfall flushes faecal contaminants from pastures and dwellings into water supplies (Hashizume et al. 2007). At the same time ongoing rainfall is often associated with decreasing diarrhoea incidence as this may lead to the flushing of sewage systems. Deeper statistical analysis is needed in order to extract signals that are caused by atmospheric conditions but are confounded by other variables. Especially precipitation and river level should be taken into account and different lag periods need to be considered.

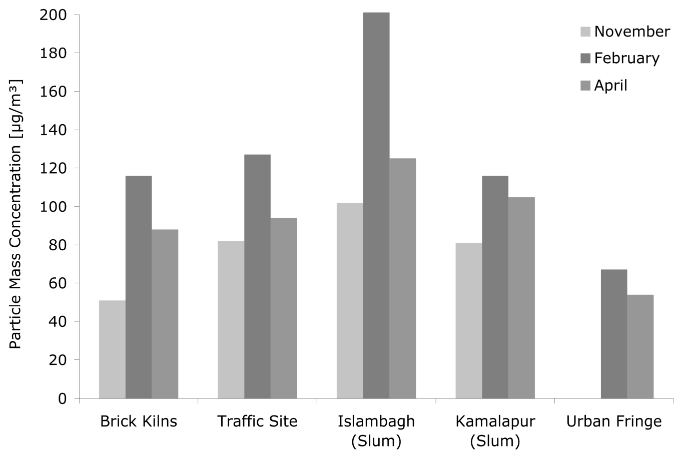

Figure 4.6: Temporal and spatial differences of particulate matter mass concentration (aerodynamic diameter from 3 to 12 micrometer) at different sites in Dhaka

Other environmental diseases showed seasonal and spatial differences as well. A decrease in hypertension during warmer months was detected. Tuberculosis cases – although comparatively rare – occur almost exclusively during the cold season. Further, tuberculosis prevalence displays clear spatial differences with some hospitals recording about five times the number compared to others. In the hospital admission data a slight increase in the occurrence of peptic ulcers during the hot season is noticeable.

Nevertheless, the interpretation of hospital admissions counts needs to be carried out carefully. Besides health status or incidence, other factors which are possibly seasonally varying might be crucial, for instance, the accessibility of the hospital, which is likely to be limited during the monsoon season, or the financial capability to pay for hospital services.

4.3.3 Discussion: Assessing the impact of climate change

Reducing current and projected burdens of climate-sensitive health determinants is a risk management issue of highest priority. Without the implementation of effective and timely options, the burden of climate-sensitive health outcomes is expected to increase with increasing climate change. In order to make educated decisions and develop appropriate mitigation strategies, policy makers require information about the likely direction and magnitude of effects on human health and their interactions with and modifications by non-climatic influences. Our research approach aims to identify climate-sensitive diseases and health outcomes and evaluate and appraise future implications for public health arising from a changing climate. One fundamental source of uncertainty in projecting the health impacts of climate change lies in the modeling of future climate development and, in particular, in the modeling of the future regional climate (IPCC 2007). Climate change does not predominantly imply an increase in the average temperature but a change of weather patterns, weather variability, extreme temperatures and extreme events (IPCC 2007). Further, the translation of climate change as a global force into its regional impact and outcome depends largely on local conditions and circumstances (e.g., socio-economic conditions, cultural adaptation). The risks are higher amongst populations with a lower level of income, particularly in developing (sub)tropical countries (Hajat et al. 2005; Hajat et al. 2006; Roth 2007). Although climate change is a global phenomenon, its physical manifestation in the world's different regions and meso-climates is highly variable. The impacts of climate change are subject to the highly dynamic and complex forces of global change (Figure 4.1). Notable examples are changing population characteristics, economic conditions and changing cultural practices. The projection or extrapolation of short-term or geographic relationships between climate and diseases to the process of long-term climate change involves uncertainties, as impacts of more gradual processes may either be more or less severe (Campbell-Lendrum and Woodruff 2006). The sum of the effects of climate change may be greater than simply an accumulation of smaller effects. It is likely that these processes involve many and various synergies and surprises with feedback mechanisms that are difficult to anticipate. Direct changes in the risk of a disease or its effects on health may be influenced by indirect changes across other sectors, e.g., water resources, land use or agriculture. Such cross-sectional changes may have adverse or ameliorative effects. Understanding the health effects of climate change requires the integration of these broad aspects. Additionally, it remains uncertain how quickly populations will adapt physically and sociologically to the steadily rising, but highly variable, temperature trends which are predicted for the coming decades. What is certain is that any attempt to address such questions requires a multidisciplinary approach and scientific efforts in the realm of climate and health modeling. Closer collaboration between climate scientists and health communities is essential to provide the focused knowledge necessary for policy and decision makers. Possible solutions need to take into consideration technical viability, human and financial resources, compatibility with current policies and other constraints. For the evaluation process, the integration of different disciplines and the solicitations of experts appear feasible.

4.4 CONCLUSIONS

Health hazards arising from a changing climate pose a serious risk management issue. In order to reach a better understanding of and to cope with this matter, further research into the interdependencies between human health and the atmospheric environment is vital, as well as research into the long- and short-term changes of climate. As the majority of populations which will be affected live in countries of the developing world, research should focus on this geographical region and deal with the specific problems arising there. However, health and climatological data for these countries is often hard to access, incomplete or of bad quality. Furthermore, the public health situation is subject to the highly dynamic processes of global change, the consequences and implications of which are difficult to anticipate. Due to the highly complex nature of this research and the policy matter involved, there is an urgent need for an interdisciplinary approach uniting atmospheric science, epidemiology, and the social and political science.

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Special thanks are due to *Prof. Dr. Mohammed Kabir, Dr. Mubarak Khan, Dr. Purabi Ahmed* and *Dr. Sharmin Khan* for the fruitful cooperation and support which they provided during the field work phases in Dhaka. Further, the authors would like to thank the German Research Council for funding the research project "INNOVATE" in Dhaka (under DFG Priority Programme 1233).

Summary: Assessing the Atmospheric Impact on Public Health in the Megacity of Dhaka, Bangladesh

Climate and air pollution (atmospheric environment) have a major impact on human health and well- being. The human body is affected by a complex system of different meteorological and air quality conditions, whereby additive and synergetic effects are very likely. The heat-mortality and -morbidity relationship varies across time periods, regions and populations. The underlying reasons for these differences remain only partially understood. In addition to the modifying effects of air pollution, there is scientific evidence that socio-economic and cultural factors play an important role in the atmospheric impact. Global climate change will have profound effects on the heat-morbidity and -mortality relationship, aggravating the public health situation for most regions worldwide. However, densely populated urban areas and so-called megacities in the developing world could suffer the most due to their high concentration of a susceptible population, their often risk-aggravating environmental conditions and low socio-economic standards. As the majority of populations affected will be living in countries of the developing world the focus should be in this geographical region dealing with the specific problems arising there. Our research aims at the identification of climate-sensitive diseases and health outcomes and the evaluation and appraisal of future implications for public health arising from a changing climate. Initially, a set of data was compiled comprising atmospheric and health information. Atmospheric data included meteorological measurements and air quality measurements. In addition, hospital admission data were collected from clinics providing service to the urban poor. Preliminary results show that there are seasonal and spatial differences in the occurrence of diseases in urban poor population groups. Acute respiratory diseases show higher incidence during the cold and dry season while for diarrhoeal disease no clear pattern could be observed. Deeper statistical analysis is needed in order to extract signals that are caused by atmospheric conditions but confounded by other variables.

Zusammenfassung: Erfassung des atmosphärischen Einflusses auf die öffentliche Gesundheit in der Megastadt Dhaka, Bangladesch

Klima und Luftverschmutzung haben tief greifende Auswirkungen auf die Gesundheit und das Wohlbefinden des Menschen. Auf den menschlichen Körper wirkt ein komplexes System verschiedener meteorologischer und luftchemischer Zustände, wobei additive und synergetische Effekte sehr wahrscheinlich sind. Die Hitze-Morbiditäts- und -Mortalitäts-Beziehung schwankt über verschiedene Zeitspannen, Regionen sowie Bevölkerungsgruppen. Die zugrunde liegenden Mechanismen für diese Unterschiede sind bisher nur teilweise verstanden. Neben dem modifizierenden Einfluss der Luftverschmutzung gibt es wissenschaftliche Belege, dass sozioökonomische und kulturelle Faktoren eine wichtige Rolle spielen. Außerdem wird der globale Klimawandel die Hitze-Mortalitäts- und Morbiditäts-Beziehung tief greifend verändern, wobei für viele Regionen der Welt eine Erhöhung der Krankheitslast zu erwarten ist. Besonders dicht besiedelte Agglomerationen und so genannte Megastädte in Entwicklungsländern werden aufgrund ihrer hohen Konzentration an vulnerabler Bevölkerung, ihren niedrigen sozioökonomischen Standards und ihrer meist erheblichen Umweltverschmutzung am stärksten betroffen sein. Da ein Großteil der betroffenen Bevölkerung in Schwellen- und Entwicklungsländern lebt, sollte der wissenschaftliche Fokus in diesen Regionen liegen und sich mit den dort spezifischen Problemen befassen. Die Arbeit beschäftigt sich mit der Identifizierung klimasensitiver Krankheiten sowie der Bewertung der Auswirkungen des Klimawandels für die menschliche Gesundheit. Zunächst wurde ein Satz aus klimatologischen Daten und Gesundheitsdaten erstellt. Die klimatologischen Daten umfassen meteorologische Informationen sowie Luftqualitätsmessungen. Zusätzlich wurden die täglichen Krankenhausaufnahmen aus Kliniken, die eine Gesundheitsversorgung für die arme städtische Bevölkerung anbieten, aufgenommen. Erste Ergebnisse deuten darauf hin, dass räumliche und zeitliche Unterschiede im Auftreten verschiedener Krankheiten bestehen. Akute Atemwegsinfekte weisen während der kalten und trockenen Jahreszeit eine höhere

Inzidenzrate auf. Hingegen war bei Durchfallerkrankungen kein klares Muster erkennbar. Weiter statistische Analysen sind notwendig, um Signale zu identifizieren, die zwar durch atmosphärische Einflüsse hervorgerufen, jedoch von anderen Effekten überdeckt werden.

Résumé: Étude de l'impact atmosphérique sur la santé publique dans la mégapole de Dhaka, Bangladesh

Le climat et la pollution atmosphérique influencent profondément la santé et le bien-être des hommes. Le corps humain est soumis à des influences complexes provenant des paramètres météorologiques et de la pollution de l'air. Il en résulte probablement des effets additifs et synergétiques. La relation entre la chaleur et la mortalité et morbidité varie selon les périodes, les régions et la population. On en comprend les causes sous-jacentes seulement en partie. A part des effets de la pollution atmosphérique, il est évident que les facteurs socio-économiques et culturels jouent aussi un rôle majeur. En plus, le changement climatique global est en train de changer les relations entre climat et mortalité ainsi que climat et morbidité et affectera la santé publique dans beaucoup de régions du monde. Les agglomérations urbaines avec une population dense et les mégacités dans les pays en voie de développement seront les plus touchés ; c'est ce qui résulte de la haute concentration de la population sensible, les mauvais standards socio-économiques et la pollution grave. Du fait que la majorité de la population affectée habite dans les pays en voie de développement, il est important que l'intérêt scientifique se focalise sur ces régions avec leurs problèmes spécifiques. Le sujet de l'article est l'identification des maladies sensibles au climat ainsi que l'évaluation et l'estimation des conséquences du changement climatique pour la santé humaine. D'abord, on a créé une série de données climatiques et sanitaires. Parmi les données climatiques on a assemblé des données atmosphériques et de la qualité de l'air. Puis, nous avons étudié les accueils quotidiens des cliniques qui soignent la population urbaine pauvre. Les premiers résultats montrent qu'il y a des différences spatiotemporelles dans l'apparition des

maladies. Les maladies respiratoires sont plus fréquentes pendant la saison froide et sèche. En ce qui concerne les diarrhées, on n'a pas pu trouvé de relations claires. D'autres analyses statistiques seront nécessaires pour discerner mieux les interdépendances.

CHAPTER 5: SEASONAL VARIATIONS OF ALL-CAUSE AND CAUSE-SPECIFIC MORTALITY BY AGE, GENDER, AND SOCIO-ECONOMIC CONDITION IN URBAN AND RURAL AREAS OF BANGLADESH

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ABSTRACT

Background

Mortality exhibits seasonal variations, which to a certain extent can be considered as mid-to long-term influences of meteorological conditions. In addition to atmospheric effects, the seasonal pattern of mortality is shaped by non-atmospheric determinants such as environmental conditions or socioeconomic status. Understanding the influence of season and other factors is essential when seeking to implement effective public health measures. The pressures of climate change make an understanding of the interdependencies between season, climate and health especially important.

Methods

This study investigated daily death counts collected within the Sample Vital Registration System (VSRS) established by the Bangladesh Bureau of Statistics (BBS). The sample was stratified by location (urban vs. rural), gender and socioeconomic status. Furthermore, seasonality was analyzed for all-cause mortality, and several cause-specific mortalities. Daily deviation from average mortality was calculated and seasonal fluctuations were elaborated using non parametric spline smoothing. A seasonality index for each year of life was calculated in order to assess the age-dependency of seasonal effects.

Results

We found distinctive seasonal variations of mortality with generally higher levels during the cold season. To some extent, a rudimentary secondary summer maximum could be observed. The degree and shape of seasonality changed with the cause of death as well as with location, gender, and SES and was strongly age-dependent. Urban areas were seen to be facing an increased summer mortality peak, particularly in terms of cardiovascular mortality. Generally, children and the elderly faced stronger seasonal effects than youths and young adults.

Conclusion

This study clearly demonstrated the complex and dynamic nature of seasonal impacts on mortality. The modifying effect of spatial and population characteristics were highlighted. While tropical regions have been, and still are, associated with a marked excess of mortality in summer, only a weakly pronounced secondary summer peak could be observed for Bangladesh, possibly due to the reduced incidence of diarrhoea-related fatalities. These findings suggest that Bangladesh is undergoing an epidemiological transition from summer to winter excess mortality, as a consequence of changes in socioeconomic conditions and health care provision.

5.1 BACKGROUND

Seasonality of mortality and, in general, of disease is a well-known phenomenon in many regions and countries worldwide. Numerous studies have been conducted in industrialized countries of the mid-latitudes (Rosenwaike 1966; Hernández and García-Moro 1986-1987; Douglas et al. 1991; Mackenbach JP et al. 1992; Gemmell et al. 2000; Feinstein CA 2002; Rau 2006) that relate a multitude of causes of death to seasonal incidence (e.g., cardio-respiratory diseases, infectious disease, diarrhoea and cholera) (Momiyama 1987; Cadet et al. 1994; Villa et al. 1999; Chung-Jen et al. 2000; Bouma and Pascual 2001; Rau 2006; Akanda et al. 2009). Likewise, seasonal fluctuations have been observed for tropical climates (Becker 1981; Madrigal 1994; Jaffar et al. 1997; Becker and Weng 1998; McMichael et al. 2008), despite the less-pronounced intra-annual climatological variation that is mainly related to seasonal differences in precipitation. Nevertheless, the number of studies focusing on tropical climates is limited, especially for Asian countries.

Although seasonal variations are to some extend driven by seasonal variations in weather, they underlie various non-atmospheric influences. These influences have fundamentally modified the shape of the seasonal pattern over recent centuries (Sakamoto-Momiyama 1978; Keatinge et al. 1989; Kunst et al. 1990; Seretakis et al. 1997; Rau 2006). In developed countries, a shift from a summer peak in mortality towards a winter peak has been observed. In contrast, tropical countries have been, and still are, associated with excess summer mortality; this is often explained by a high prevalence of infectious and diarrhoeal disease. The modifying effect of non-atmospheric parameters is well-demonstrated by the existence of different seasonality regimes within the same climatic region. For instance, major differences between urban and rural areas could be observed in France in the 18th century (Bideau et al. 1988), and were also found between White and Afro-American groups in Philadelphia in the same century (Klepp 1994). In a more recent study, education serving as a proxy for socioeconomic status has been highlighted as a determinant for seasonal fluctuations of mortality (Rau 2006).

Apart from climate, cultural and behavioural aspects apparently play a major role in shaping the seasonal distribution of mortality (The Eurowinter Group 1997, 2000). Paradoxically, studies show that countries with a relatively warm or mild winter climate, such as Spain, Portugal, Italy, or the UK and Ireland, experience much greater excess winter mortality than countries with harsh climatic conditions during winter, such as Finland, Norway, or Russia (Siberia) (The Eurowinter Group 1997; Rau 2006). Better adjustment and social adaptation to the cold in countries with cold winter climates have been cited as explanations. There is evidence that with the same outdoor temperatures, people living in colder climates wear warmer clothes and protect themselves better against the cold (The Eurowinter Group 1997; Donaldson et al. 1998a; Donaldson et al. 1998b; The Eurowinter Group 2000).

Understanding the impact of seasonally varying factors, the effects of atmospheric conditions and the modifying effect of non-atmospheric influences can make a contribution to establishing effective public health measures. Whereas in a recent study (Burkart et al. 2011a) we investigated the short-term effects of thermal conditions, this study seeks to asses mid-to long-term seasonal effects and atmospheric influences. To date, very few studies have investigated the atmosphere-mortality relationship in a tropical developing country; whereas the vast majority of all such research has concentrated on an assessment of seasonal effects rather than immediate meteorological effects. In focusing on seasonality we were able to set the findings of this work in the context of other studies thus allowing comparison of results. Moreover, conducting a multi-stratified analysis enabled us to reach a better understanding of the various non-atmospheric effect modifiers. In particular, we focused on the differences between urban and rural areas, gender differences and differences between regions with different socioeconomic status (SES). We also considered various causes of death and age-specific effects.

5.2 METHODS

Mortality data were provided by the Bangladesh Bureau of Statistics (BBS) for the period from 2002 to 2007. The data were collected within the Sample Vital Registration System (SVRS), which has existed in its current version since 2002. The SVRS comprises and surveys 1,000 Primary Sample Units (PSU) in rural and urban areas, and in the statistical metropolitan area (SMA). A PSU is a compact cluster with approximately 200 households with a household size of 4-5 members (4.7 on average). A number of 640 PSUs is located in rural areas, comprising 132,646 households; 280 PSUs are located in urban areas with 57,852 households and 80 PSU are placed in the SMA with 16,024 households. The SVRS provides information on housing, household, and population characteristics that are continuously updated. Data is collected using a dual recording system. Initially, vital events are collected by a locally-recruited recorder (System 1). Subsequently, data are collected in retrospective by a group of officials from the BBS on a quarterly basis (System 2). Afterwards, data are matched by pre-designed matching criteria and classified into matched, partially-matched and non-matched events. Partially-matched and non-matched events are subject to further verification through field visits. The following information about each fatal event was recorded: name of the deceased, date of birth, date of death and sex of the deceased. Moreover, a cause of death is attributed, which, however, is not medically certified. For further information see (Bangladesh Bureau of Statistics 2008).

For this study all accidental deaths, maternity-related deaths, data from the statistical metropolitan area, and the data of 2002 were excluded. Furthermore, we excluded deaths of infants younger than one year, as births exhibit seasonal variations which could confound our analysis. As severe flooding submerged major parts of the country in 2004, we conducted a sensitivity analysis running our analysis with and without data from this year. Results were mostly unaffected, except for diarrhoeal mortality and other-cause mortality. Therefore, the analysis on those two causes of death was done excluding deaths occurring in 2004. In total, 21,551 deaths were analyzed. Stratified-time series plots of the daily death counts are provided in an additional file (Appendix 1).

Daily mortality was defined as daily crude death rates (number of deaths per population). In order to facilitate comparison between different subcategories we calculated the percent deviation from average mortality for each day of the year from 2003 to 2007. Average daily mortality (expected mortality) was calculated separately for each year in order to account for inter-annual changes in mortality.

In order to assess the extent of seasonality and its age-specific characteristics, we calculated a seasonality index (Φ) for each year of life, defined as the ratio of the number of deaths in the months with the highest and lowest mortality (see Formula 1)

$$\phi = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{N_{Max,i}}{N_{Min,i}}\right) \qquad \text{(Formula 5.1)}$$

With Φ being the seasonality index, N_{Max} and N_{Min} the numbers of deaths in the months with the highest and lowest death counts in year *i*, and *n* the number of years from 2003 to 2007

To display seasonal variations of mortality and age-specific seasonality of mortality we smoothed the data with penalized spline (P-spline) smoothers. Unlike many other seasonality studies we chose a non-parametric smoothing approach in order to account for multi-modal seasonal distributions. Data analysis and smoothing was carried out using R (Version 2.11.0) and the R package ‘mgcv’. P-splines applied in this analysis are as proposed by Eilers and Marx (Eilers and Marx 1996).

The analysis of seasonality by SES was conducted on the administrative level of Zilas, which are subunits of the six divisions existing in Bangladesh. To distinguish between Zilas with high and low SES, we derived four socioeconomic factors by conducting a factor analysis (Varimax rotation) using R (Version 2.7.2). Variables considered for factor analysis were child mortality rate, child/woman ratio, literacy rate, fertility rate, source of drinking and non-drinking water, infant mortality, insolvency rate and use of solid fuels. At least three of the four derived factors being below or above the 50th percentile were criteria for Zilas to be categorized as either low or high SES. Of the 64 Zilas, 23 were categorized as having poor SES and 25 were categorized as having high SES. The remaining Zilas were treated as reference. Like in most developing countries differences between sub-populations are strongly pronounced, but also differences between the considered divisions were marked. The relative standard deviation for the use of surface water as drinking water reached up to 400%; also for infant and child mortality or insolvency the relative standard deviations ranged between 30 and 70%.

5.3 RESULTS

5.3.1 Causes of death

Major causes of death were respiratory diseases (~18%), cardiovascular diseases (~14%) and infectious diseases (~14%). Cancer made up approximately 6% of all deaths. Diarrhoeal disease only accounted for approximately 4%, while vector-borne diseases and malnutrition accounted for approximately 2% of all deaths on average. Approximately 18% of mortalities were classified as “old-age diseases”, and approximately 22% were not specifically classified. The distribution of cause of death varied with age (Figure 5.1). The main causes of death among children were respiratory, diarrhoeal and infectious diseases. However, these causes declined for juveniles and older persons, and other causes of death, such as cancer and cardiovascular diseases, became more dominant.

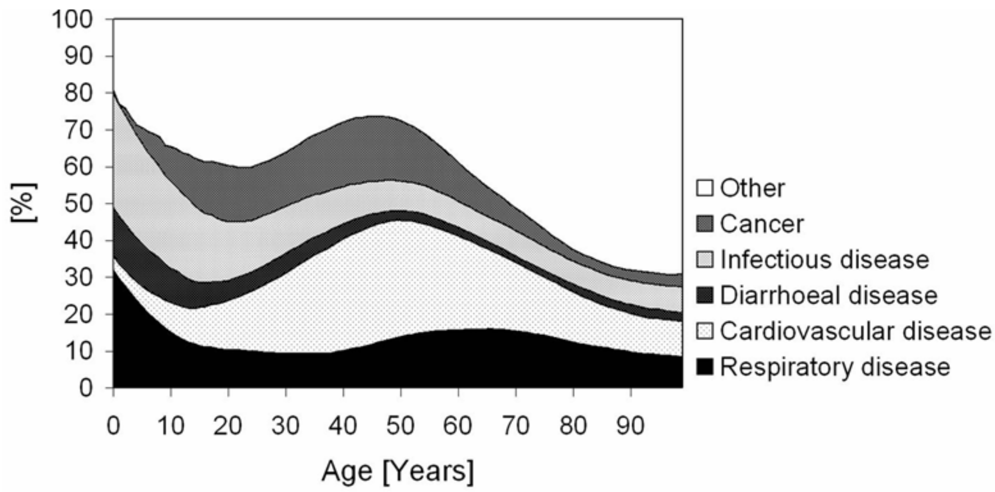

Figure 5.1: Age-dependency of causes of death

Besides the age-dependency of the distribution of cause of death, we found differences between urban vs. rural areas, between males vs. females, and between regions with high vs. low SES (Table 5.1). The Chi-square test was applied to determine whether the probability of dying from a particular disease was significantly different between two categories (rural vs. urban, male vs. female, high vs. low SES). The risk of dying from respiratory, diarrhoeal, infectious or vector-borne disease was significantly higher in rural areas, while in urban areas the risk of dying from cardiovascular disease or cancer was higher. Likewise, significant differences were found between males and females with increased probability in males of dying from respiratory or cardiovascular disease and females dying from diarrhoeal and infectious disease or malnutrition. In low SES regions a higher probability of dying from diarrhoeal disease was observed whilst in high SES regions the probability of dying from cardiovascular disease was higher.

Table 5.1: Percentage of deaths attributed to selected diseases by location, gender and socio-economic status (SES) (2003-2007)

Cause of death	Rural	Urban	p-value*	Male	Female	p-value*	Low SES	High SES	p-value*
Respiratory disease	19.4	16.1	<0.001	19.4	17.0	<0.001	14.1	14.2	0.95
Cardiovascular disease	11.5	20.8	<0.001	16.7	11.0	<0.001	14.7	17.6	<0.001
Diarrhoeal disease	3.9	2.7	<0.001	3.2	4.1	<0.001	3.5	2.9	0.02
Infectious disease	13.9	9.4	<0.001	12.2	13.7	<0.001	10.1	10.5	0.36
Cancer	6.2	7.5	<0.001	6.7	6.3	0.16	7.1	7.7	0.13
Malnutrition	2.0	1.8	0.24	1.7	2.4	<0.001	1.1	0.7	0.10
Vector-borne disease	1.5	0.7	<0.001	1.4	1.3	0.39	1.3	1.4	0.05
Other diseases	41.6	41.0	0.01	38.7	44.2	<0.001	48.1	45.0	<0.001
Total	100	100		100	100		100	100	

*: p-values were determined by Chi-square tests with a significance level of 0.05.

5.3.2 Seasonal variations of all-cause mortality and cause-specific mortality

All-cause and cause-specific mortality showed a pronounced seasonality, except for cancer. For our further analysis of cause-specific seasonality we focused on respiratory, cardiovascular and diarrhoeal mortality. Analyses for other causes of death are included in an additional file (Appendix 1), but will not be discussed due to the complexity of disease pathogenesis and multitude of causative agents, particularly in the case of infectious and other disease mortality. All-cause mortality exhibited a marked seasonality with a bimodal distribution. The primary maximum occurred during the cold and dry season (October to February), and the secondary maximum was from May to July, at the end of the summer season and the beginning of the monsoon season (Figure 5.2). With regard to different disease groups, marked seasonal variations could also be observed, with the shape of the seasonal distribution being determined by location, gender, or SES. Generally, respiratory and cardiovascular mortality were highest during the cold season, with some strata showing increased levels during summer. Seasonal fluctuations in diarrhoeal mortality varied heavily by investigated category, with no seasonal pattern or multiple seasonal peaks and troughs occurring during the year.

5.3.3 Seasonal variations by location, gender, and SES

A greater excess of all-cause mortality in summer was evident in urban areas than in rural areas, while winter excess mortality was equally high in both areas (Figure 5.2). For females and regions with high SES slightly stronger seasonal fluctuations were observed, originating mainly from a strong negative deviation of mortality during the monsoon season. Deaths from respiratory diseases generally peaked during the cold season, with a small secondary maximum during summer for males (Figure 5.2). In urban and high SES areas, respiratory seasonality was only minor. Cardiovascular mortality was generally higher during the cold winter season. Nevertheless, urban areas exhibited a pronounced secondary summer maximum of cardiovascular mortality. In areas with high SES, a small summer maximum was observed as well (Figure 5.2).

Diarrhoeal mortality showed the most complex seasonal variations. In general, two maxima occurred: one between the summer and the beginning of the monsoon season, and the other at the end of the monsoon season. However, size and exact temporal occurrence varied with location, gender and SES (Figure 5.2). In rural areas a primary peak from April to June occurred and a secondary peak at the end of the rainy season. Additionally, rural diarrhoeal mortality was increased during winter, in December and January. In urban areas some sort of a post-monsoon maximum, with slightly increased levels from September to December was observed. However, variations in urban areas were only minor (Figure 5.2). For males a marked primary peak from March to June and a less marked secondary maximum at the end of the monsoon season were detected. In the case of females, no seasonal pattern of diarrhoeal mortality emerged. In regions with low SES, two equally pronounced maxima occurred: one in summer and one at the end of the monsoon season. In regions with high SES, diarrhoeal mortality was slightly increased at the end of the monsoon season and diminished during winter.

5.3.4 Age-dependency of seasonality

For all considered diseases, the magnitude of seasonality represented by the seasonality index (Φ) was strongly age-dependent (Figure 5.3). Generally, children faced a high magnitude of seasonality while for youths and young adults seasonality was less important. With progressing age, the magnitude of seasonality rose again and reached maximum levels at the age of 60 to 80 years. Above this age, seasonality declined again. Respiratory seasonality was strongly pronounced for children and additionally pronounced for older age groups between 40 and 80. Particularly, children and the elderly in rural areas, as well as elderly males, faced a strong seasonal risk. Cardiovascular seasonality played no role for children, but was pronounced for persons aged between 40 and 80 years, peaking at the age of 60. Predominantly males and regions with high SES were subject to strong seasonal effects on cardiovascular mortality in the elderly. In the case of diarrhoeal mortality, seasonality mainly played a role for children in their first years of life and then rapidly subsided. Diarrhoeal child mortality was particularly subject to seasonality in rural areas, in males and in regions with low SES.

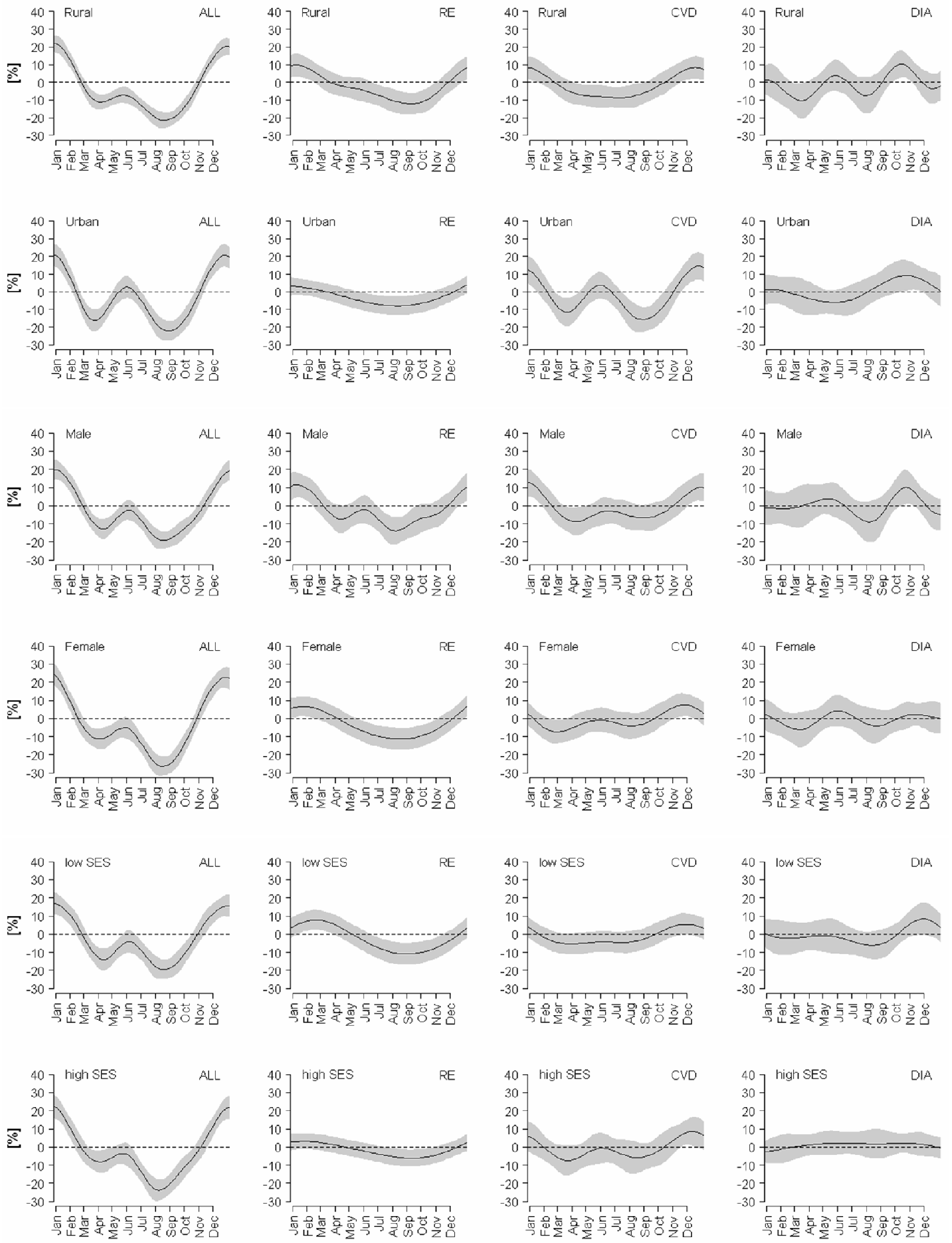

Figure 5.2: Annual seasonal mortality variations of all-cause mortality (ALL), respiratory mortality (RE), cardiovascular mortality (CVD), and diarrhoeal mortality (DIA) distinguished between different subcategories (rural vs. urban, male vs. female, low vs. high SES). The 95%-confidence intervals are displayed by the shaded areas

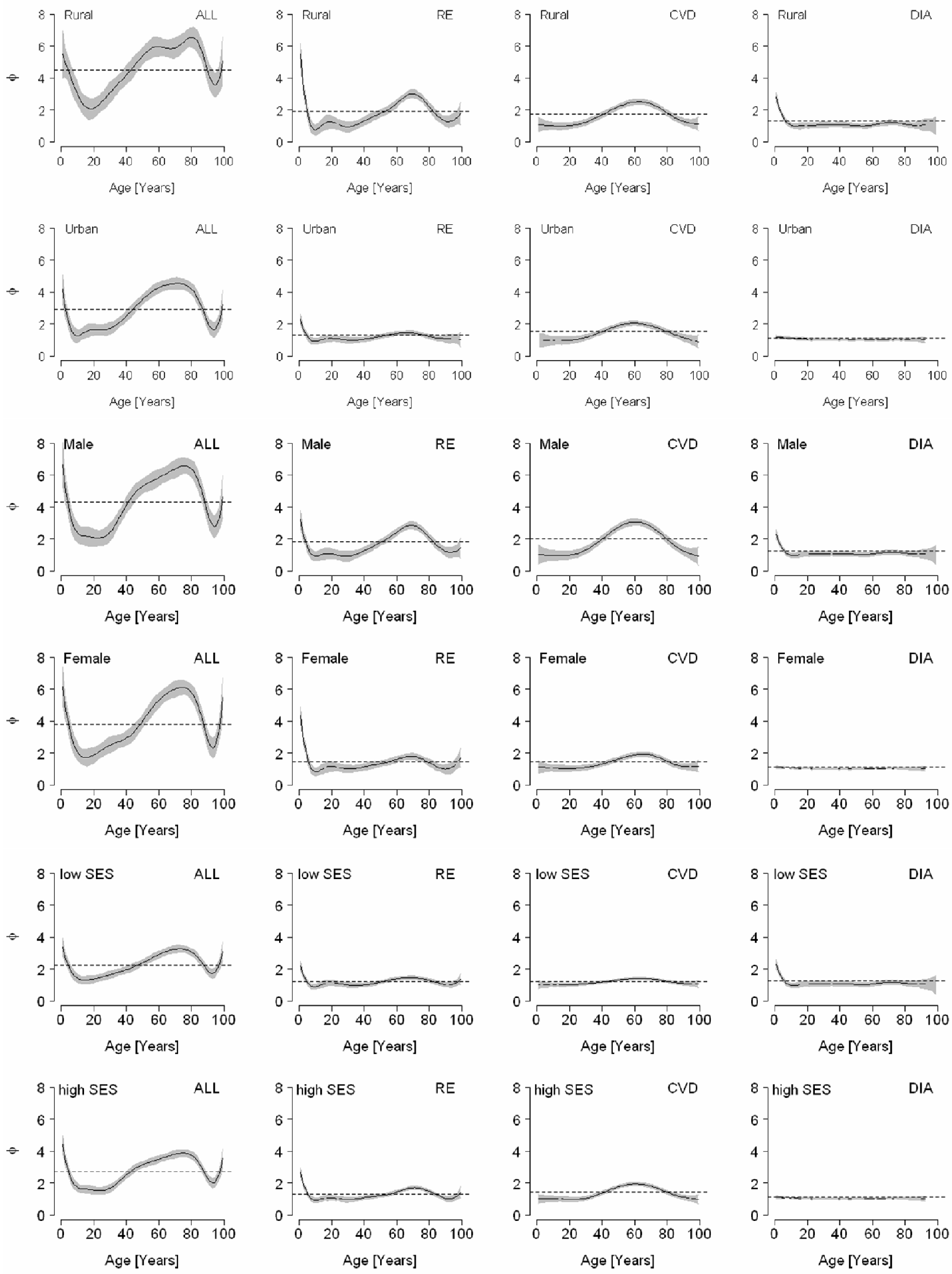

Figure 5.3: Age-dependency of seasonality of all-cause mortality (ALL), respiratory mortality (RE), cardiovascular mortality (CVD), and diarrhoeal mortality (DIA) distinguished between different subcategories (rural vs. urban, male vs. female, low vs. high SES). Mean of seasonality index is indicated by the dashed lines. The 95%-confidence intervals are displayed by the shaded area

5.4 DISCUSSION

5.4.1 General findings and conclusions

In this study we identified distinct seasonal variations of mortality, with the shape of the seasonal pattern depending on the cause of death, age, gender, and location, as well as SES. Unlike findings from other tropical regions (McGregor et al. 1961; Ruzicka and Kanitkar 1973; Victoria et al. 1985; Underwood 1991; Madrigal 1994; Motohashi et al. 1996; Jaffar et al. 1997; Delaunay et al. 2001; Etard et al. 2004; Rayco-Solon et al. 2004; McMichael et al. 2008), we did not find a primary maximum in mortality during the hot and humid/rainy season. In our data the summer excess mortality may have been represented by the secondary maximum from April to June. However, the main peak in mortality occurred during the cold season. This observation suggests that Bangladesh is undergoing an epidemiological transition as the incidence of diarrhoeal deaths reduces considerably and cardio-respiratory diseases become more dominant. A transition in the seasonal pattern - from a summer to a winter peak - has also been described for Europe and Japan, and SES changes and improved medical care served as explanations (Sakamoto-Momiyama 1978; Rau 2006). Indeed, a study analysing death counts from 1972-1974 from a rural area in Bangladesh found a winter maximum for dysentery and chronic diarrhoeal mortality. The author ascribed this pattern to the high quality of diarrhoeal health care in that particular (intervention) area and acknowledged that such a mortality pattern is possibly not found in other areas (Becker 1981). In a follow-up study, in which data from 1982 to 1990 was analyzed, a winter maximum was still found for all-cause mortality; however, diarrhoeal deaths peaked during the hot and humid season (Becker and Weng 1998). To date, the only lower-latitude regions exhibiting a mortality peak during the cold season are Mexico City (Mexico) and São Paulo (Brazil), both located within higher altitudes and exhibiting temperate climatic conditions (type C-climates according the Köppen-Geiger classification) as well as a generally higher SES (McMichael et al. 2008). Moreover, a higher mortality during the cold months was found for under-five mortality in Nairobi (Kenya), also classified as a temperate type C-climate (Ye et al. 2009; Mutisya et al. 2010). To our knowledge, the only country with a tropical type A-climate for which a winter excess mortality has been established is Bangladesh.

Nowadays, respiratory and cardiovascular diseases are the leading causes of death in Bangladesh. We found that both diseases as well as all-cause mortality peaked during winter, despite the perception of the relatively cold season as being thermally comfortable. These findings suggest that winter excess mortality is not a consequence of seasonal low absolute temperatures but, rather, is a consequence of a seasonal fall in average temperature. The adverse effect of relatively low temperatures was also demonstrated in a recent study using the same data set (Burkart et al. 2011a). Regression models adjusted for the confounding effects of trend, season and day of the month revealed an increase in mortality with temperatures falling below a threshold situated in the 90th to 95th percentile of the temperature distribution. While adequately adapted to heat, the Bangladeshi population seems less prepared for the winter period. The importance of relative cold is also highlighted by research conducted by Douglas et al. (1991) and the Eurowinter Group (1997).

The pronounced summer peak of all-cause and cardiovascular mortality in urban areas is possibly related to the urban excess (equivalent) temperature, the so-called urban heat island. Excess temperatures amounting to several Kelvin in monthly averages were found in urban areas of (sub)tropical regions (Roth 2007; Burkart and Endlicher 2011). Nevertheless, a higher susceptibility of the urban population towards heat might also be an explanation. A higher susceptibility towards heat might also be the cause of the secondary summer maximum of cardiovascular mortality in regions with high SES.

In this study the complexity and dynamic nature of diarrhoeal disease pathogenesis is once more illustrated. Several agents that induce diarrhoeal disease favour different meteorological and hydrological conditions for their replication and survival. High temperatures generally promote the growth of bacteria, whereas, for instance, shigella epidemics show a high incidence rate during the cold season (Hossain et al. 1990). Furthermore, there is evidence that moderate temperatures favour certain agents, such as the rotavirus (Hashizume et al. 2007; Levy et al. 2008). Additionally, hydrological aspects, such as stagnant water, a lack of dilution, contamination, or the break down of water systems associated with no, high, or ongoing rainfall, determine the spread of diarrhoeal pathogens (Hashizume et al. 2007; Zhang et al. 2007b). Cholera incidence showed a bimodal distribution in Bengal that seemed to be driven by hydroclimatological factors (Akanda et al. 2009; Hashizume et al. 2009a). Low precipitation and low river discharge during spring was associated with the first outbreaks of cholera in Bangladesh whereas high precipitation and peak streamflow of rivers during the monsoon season was associated with the second peak during the monsoon season (Akanda et al. 2009; Hashizume et al. 2009a).

Given this background information, the interpretation of our findings is complex. Nevertheless, we suggest that the summer peak in diarrhoeal mortality is predominantly caused by bacterial contamination during the hot season favouring replication of agents, whilst the post-monsoonal peak probably results from overstrained sewage systems, flooding and stagnant water. The pronounced seasonal pattern in rural areas and areas with low SES is possibly due to reduced coping abilities in these regions. The absence of a summer peak in urban areas and the reduced post-monsoonal peak might be due to improved access to fresh aliments, cooling systems as well as more developed drainage and sewage systems. Regarding female diarrhoeal mortality, the nonexistence of seasonal fluctuations is surprising as females are facing an increased risk of dying from diarrhoeal mortality. Women are usually bound to their homes consuming home made food, whilst men are commonly pursuing an income generating activity outside that forces them to eat food either self-carried or purchased at some sort of restaurant. Particularly, during the summer season the risk of bacterial contamination is thus increased. In areas with high SES, higher sanitary standards, improved water and drainage systems and higher levels of education might have resulted in reduced diarrhoeal seasonality.

Our analysis further showed that seasonality is strongly age-dependent. Children in their first years of life exhibited a high magnitude of seasonality, demonstrating their susceptibility towards environmental conditions. This susceptibility to season and environment was even more pronounced in rural areas, probably resulting from poor primary health services as well as poor living standards. Although young and middle-aged adults are likely to be most excessively exposed to environmental influences they were the only group to show weak or no seasonality. The increasing seasonality index with increasing age reflects the growing susceptibility of the human organism towards environmental conditions. The observed decrease in seasonality between the ages of 80 and 90 might be due to the so called selection effect, described in detail by Rau (Rau 2006). Briefly, the phenomenon is the consequence of a heterogeneous population in which frail individuals face higher mortality, leaving a robust subset. This robust subset is less susceptible to seasonal effects, lowering seasonality up to a certain age beyond which individuals once again become more susceptible.

5.4.2 Strengths and limitations

Compared to studies conducted in Western countries, our data comprise only a sample and not a complete inventory. Nevertheless, in the context of a developing country such data availability is rather exceptional as the data set includes continuous data and covers Bangladesh on a nationwide level. Incompleteness, underreporting and the absence of validation and correction of known bias are often associated with civil registration systems in developing countries (Huy et al. 2003; Mahapatra et al. 2007). Due to the dual recording system the authors appraise the reliability of the data as rather high. Although in other cases difficulties are imposed by the fact that many deaths occurring at home in resource-poor countries are not registered (Setel et al. 2005), here this is bypassed by the registration system, which surveys households. However, some limitations should be mentioned. One of the limitations is related to the lack of information about the socioeconomic composition of the sample. Bangladeshi society consists of a wide range of different groups with different socioeconomic and educational backgrounds. Furthermore, the data collection and registration were not medically certified and cause of death classification is rather rough and does not follow International Classification of Disease standards. Our analysis revealed that the magnitude of seasonality is strongly age-dependent; however, this finding does not allow conclusions about the temporal occurrence of maximum or minimum mortality. It may well be that the seasonal pattern reveals to be modified for different age groups with temporally displayed peaks and troughs compared to the mean seasonal pattern. The number of observations, however, did not allow a further age stratification of the seasonality plots, particularly not in the case of cause-specific mortality. Finally, we need to acknowledge that due to the nature of this ecological study which is based on aggregated information, inferences need to be made carefully as the risk of ecological fallacy is implied.

5.5 CONCLUSIONS

This study demonstrated the importance of considering seasonal impacts on mortality and revealed several target groups and diseases for which the consideration of seasonality seems particularly crucial. We showed that the effect of season or seasonally changing environmental conditions depends on preconditions in a subpopulation or region. In particular, rural areas showed a high magnitude of infant and child seasonality, while urban areas were strongly associated with summer excess mortality, especially for cardiovascular mortality. Children and elderly people were affected most by seasonal effects. The consideration of such seasonal effects could help to place public health interventions most effectively. Generally, protection measures against cold or heat among infants or those under hospital care can help to avoid or overcome critical states of health. We emphasise that knowledge on the interaction between seasons, atmosphere, and health is especially necessary in times of climate change so that its possible impacts can be mitigated.

ACKNOWLEDGEMENTS

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COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHORS' CONTRIBUTIONS

KB developed the research design and analytical approach, performed the statistical analysis, and wrote the entire the manuscript. WE, MHK and AK assisted with the research design and critically reviewed the manuscript and discussed the findings and interpretation. SB and AK contributed to the statistical analysis and critically reviewed the manuscript and discussed the findings and interpretation. All authors have read and approved the final manuscript.

CHAPTER 6: THE EFFECT OF ATMOSPHERIC THERMAL CONDITIONS AND URBAN THERMAL POLLUTION ON ALL-CAUSE AND CARDIOVASCULAR MORTALITY IN BANGLADESH

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ABSTRACT

This study assessed the effect of temperature and thermal atmospheric conditions on all-cause and cardiovascular mortality in Bangladesh. In particular, differences in the response to elevated temperatures between urban and rural areas were investigated. Generalized additive models (GAMs) for daily death counts, adjusted for trend, season, day of the month and age were separately fitted for urban and rural areas. Breakpoint models were applied for determining the increase in mortality above and below a threshold (equivalent) temperature. Generally, a '*V*'-shaped (equivalent) temperature-mortality curve with increasing mortality at low and high temperatures was observed. Particularly, urban areas suffered from heat-related mortality with a steep increase above a specific threshold. This adverse heat effect may well increase with ongoing urbanization and the intensification of the urban heat island due to the densification of building structures. Moreover, rising temperatures due to climate change could aggravate thermal stress.

Capsule: Mortality in Bangladesh is strongly affected by thermal atmospheric conditions with particularly urban areas facing excess mortality above a specific threshold temperature.

Keywords: Atmospheric thermo-physiolocical conditions, thermal pollution, heat effect, all-cause mortality, cardiovascular mortality

6.1 INTRODUCTION

Several studies have investigated the association between temperature and human mortality (Kunst et al. 1993; Basu and Samet 2002; Baccini et al. 2008; McMichael et al. 2008; Basu 2009). The majority of studies identified *U*- or *V*-shaped temperature-mortality curves with increasing mortality levels at high and low temperatures (ibid). Moreover, there is evidence that the effect of temperature is influenced by non-atmospheric conditions. Research findings have indicated that not only environmental but socio-economic and socio-demographic variables serve to modify the effects of temperature (e.g., Medina-Ramón and Schwartz, 2007; Hajat et al., 2005). Stronger heat effects in cities with a milder climate, higher population density or level of urbanization and high costs of living have been observed (Smoyer et al. 2000; Medina-Ramón and Schwartz 2007). A comparative study found that the extent of short-term mortality displacement was high in London but lower in Delhi, where infectious and childhood mortality still predominates (Hajat et al. 2005). During the Chicago heat wave of 1995, African-Americans, urban poor and those with less-developed social networks were most at risk (Klinenberg 2002; Kaiser et al. 2007).

Generally, urban populations appear to be more vulnerable to the effects of heat (Smoyer et al. 2000). Differences in socio-economic conditions, lifestyles and pre-existing health conditions between rural and urban areas might be possible explanations for this phenomenon. Furthermore, the anthropogenic modification of the urban mesoclimate, the so-called urban heat island (UHI) is likely to increase thermal stress and have an adverse effect on human health. Urbanization is especially prevalent in developing countries (United Nations 2008). Worldwide, the number of people living in urban areas is increasing. According to United Nations projections, the rate of urban population change from 2010 to 2025 is set to register 2.1% in less developed and 3.8% in the least developed countries, compared with 0.6% in developed countries. For Bangladesh in particular, the projected growth rate is 3.0% (United Nations 2008, 2010).

The majority of research on thermal effects has been conducted in industrialized countries located in the mid-latitudes, whereas little is known about the temperature-mortality relationship in less developed and especially in tropical countries (Hashizume et al. 2007; McMichael et al. 2008). Considering the modifying effect of non-atmospheric variables, the insights gained from studies conducted in temperate climate zones cannot be directly applied to tropical climates. Moreover, most recent studies focused on the impact of temperature with several also controlling for humidity. However, in addition to temperature, the human heat budget is affected by humidity, air movement and short- and long-wave radiation fluxes (Steadman 1979; Fiala et al. 1999; Höppe 1999; Fiala et al. 2001; Jendritzky et al. 2007). In this context, reducing thermal effects to temperature effects fails to address the complexity of the question.

This study assessed the impact of thermal conditions on mortality in Bangladesh, considering all physiologically relevant meteorological parameters. We contrasted findings from urban areas with those from rural areas in order to investigate differences in the response to heat. Of particular interest was whether urban populations face a higher risk of heat-related mortality. We determined the threshold values above and below which a rise in mortality occurred and the percentage increase beyond these thresholds. Furthermore, we investigated the suitability of different atmospheric indices as predictors of mortality.

6.2 MATERIAL AND METHODS

6.2.1 Meteorological data

Meteorological data, from January 2003 to December 2007, comprising three-hourly values of temperature, humidity, wind speed, and cloud coverage were collected by the Bangladesh Meteorological Department for 26 stations across Bangladesh. Daily mean and extreme values were calculated for each station as far as the measurements were complete for a given day. Approximately 17% of the daily calculated data were missing over all stations. Missing daily values of temperature or thermo-physiological indices (TPIs) were replaced by linear interpolation. If three quarters of the daily values for a month were available, we calculated monthly values to perform the bioclimate and heat island assessment (10% of the monthly values were missing). The magnitude of the urban heat island was calculated as the differences in the monthly average values between an urban station in Dhaka and a rural reference station in Mymensingh, located approximately 120 km from Dhaka.

As meteorological stations were highly correlated and the differences between stations were only minor, Bangladesh was taken as representing one single climate regions (for detailed information on regional climate assessment we refer to the Supplementary Material (Appendix 2)). Regional meteorological variations were not considered and a spatial average daily mean value was calculated for the regression analysis. Spatial (equivalent) temperature maps were generated for each day using inverse distance interpolation (R, Version 2.11.0, package 'gstat'). Following, a mean value was calculated from the map grid values. The spatial aggregation helped to increase the statistical power and significance of the regression analysis but left meso- or micro-scale specifications unaccounted for.

6.2.2 Thermo-physiological modeling

Different TPIs were calculated based on the three-hourly values using so called thermo-physiological models. Human thermoregulation is basically determined by metabolic heat production and energy transfer with the surrounding environment. The magnitude and efficiency of energy exchange between a body and its surroundings is determined by meteorological conditions; primarily through the ambient temperature, but humidity, air movement, and long- or short-wave radiation also exert influence. Thermo-physiological models are used to model the complex interactions between external energy gain, physiological reactions of the human organism, and body-environment energy exchange (Steadman 1979; Höppe 1999; Fiala et al. 2001; Parsons 2003). The output variables of these models are equivalent temperatures which are temperatures resulting in the same energy gain or loss like under a reference atmospheric environment. This paper uses the terms thermo-physiological index and equivalent temperature synonymously. Three different TPIs were calculated for this study.

The Heat Index (HI) combines air temperature and humidity in order to account for the diminished latent energy release following higher atmospheric water vapor pressure (reference environment: temperature 25°C; humidity 50%) It is an index assessing heat (not cold) and is defined for temperatures above 26°C and a relative humidity above 40% (Steadman 1979). The HI was calculated whenever threshold criteria were met; whenever no index was calculated, the measured air temperature was retained.

The physiological equivalent temperature (PET) is based on the Munich Energy-balance Model for Individuals. PET is defined as the air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed (reference environment: temperature 20°C, humidity 50%) (Höppe 1999). PET requires the input parameters temperature, humidity, mean radiation temperature and wind speed.

The universal thermal climate index (UTCI) is based on the Fiala model (Fiala et al. 1999; Fiala et al. 2001) - a thermo-physiological model which has been extensively validated using experimental data from numerous groups (Jendritzky et al. 2007). The model accounts for heat transfer occurring inside the human body and at its surface. Additionally, it simulates responses of the human thermoregulatory system. A reference environment with 50% relative humidity, still air, and a radiant temperature equaling air temperature is defined. The input variables are temperature, humidity, wind speed and mean radiation temperature. To determine PET and UTCI, the input variable mean radiant temperature (uniform temperature of a surrounding surface which results in the same radiation energy gain on a human body as the prevailing radiation fluxes) is modeled as a function of temperature and cloud coverage using RayMan (Version 1.2) (Matzarakis et al. 2007). All models contain certain but similar assumptions about the human body mass and height, clothing and the amount of physical activity undertaken.

6.2.3 Mortality data

Mortality data from January 2003 to December 2007 based on the Sample Vital Registration System (SVRS) was provided by the Bangladesh Bureau of Statistics (BBS). The SVRS comprises 1 000 primary sample units (PSUs), from which 640 PSUs are located in rural areas, 280 in urban areas and 80 in the statistical metropolitan area. A PSU is a compact cluster of around 250 households, each with 4-5 household members. Approximately one million individuals, living in 206 552 households, fall under the scope of this monitoring program. The SVRS continually collects vital events, such as deaths under a dual recording system. Initially, events are registered by a locally-recruited recorder as they occur. Additionally, data is collected in retrospective by officials from the BBS on a quarterly basis. Both data sets are matched by pre-designed matching criteria in order to assure a high reliability of the data (Bangladesh Bureau of Statistics 2008). A more detailed description of the mortality data and the SVRS is provided in the Supplementary Material (Appendix 2). For the purposes of this study, accidental deaths, maternity related deaths and infant deaths were excluded. As a primary objective of this study was to contrast the temperature-mortality relationship in urban vs. rural areas we did not include the statistical metropolitan area in our analysis. The statistical metropolitan area cannot be considered typically urban or typically rural. Crude death rate and age-adjusted mortality rates were determine for urban and rural areas (information on age-adjustment of mortality rates is provided in the Supplementary Material (Appendix 2)).

6.2.4 Statistical methods

The association between daily death counts and ambient temperature, HI, PET, or UTCI was analyzed using Poisson generalized additive models (GAMs) allowing for linear and non-linear confounding effects. The R (Version 2.11.0) package 'mgcv' was used for model fitting. In order to elaborate urban-rural differences we fitted models for urban and rural death counts separately. We investigated thermal effects on all-causes mortality and cardiovascular mortality. Cardiovascular diseases are most likely to be directly influenced by temperature. In total, we analyzed 21,655 deaths, accumulated over 5 years from 2003 to 2007. The number of urban all-cause deaths amounted to 6,233, of urban cardiovascular deaths to 1,484. In rural areas 15,422 all-cause deaths and 2,111 cardiovascular deaths were counted.

Penalized regression splines were used to allow for nonlinear confounding effects. Smoothing parameters were chosen to minimize the Un-Biased Risk Estimator (UBRE) score for the models. A Bayesian approach to variance estimation was employed to calculate the confidence intervals (Wood 2006). The models were adjusted for trend, season, day of the month and age. The reasoning for incorporating season into the models was to remove the mid- to long-term seasonal cycles in the series, as we aimed at investigating short-term influences. Moreover, seasonal adjustment allowed to reflect seasonal differences in air pollution levels with high levels during winter (stable atmospheric conditions) and decreasing levels in the pre-monsoon and monsoon season (labile atmospheric conditions). We distinguished between three seasons: the winter season (October to February), summer/pre-monsoon season (March to May), and the monsoon/rainy season (June to September). For age-adjustment three age groups were considered (1-14 years, 15-44 years, 45+ years). Due to the limited number of death counts, age-adjustment could not be done for cardiovascular deaths. We did not adjust for sex as the number of observations allowed no further stratification. However, differences in mortality by sex are rather small in Bangladesh. After incorporation of the confounder variables, plots of partial autocorrelation showed no autocorrelation and an autocorrelation term was therefore not incorporated into the final models. Humidity was not integrated separately into the models as this may result in multi-collinearity problems. Instead, humidity and other meteorological variables were accounted for by thermo-physiological indices.

Models were fitted integrating (equivalent) temperatures of the actual and the previous day (averages of lag 0-1) in order to identify heat and cold effects caused by recent thermal conditions. To account for more delayed thermal effects, models incorporating the average of daily (equivalent) temperatures and temperatures of the recent six days (averages of lag 0-6) as well as of the recent 13 days (averages of lag 0-13) were fitted.

Breakpoint models (hockey stick models) were applied to detect threshold temperatures and to quantify the effect of cold and heat. These are regression models assuming piecewise linear relationships between the response and the explanatory variable (Muggeo 2008). The regression lines are connected at unknown values called breakpoints. In this study, the breakpoints represent the temperatures above and below which the temperature–mortality relationship changes. The fitting of the breakpoint regression models was carried out with R (Version 2.11.0) and the R package 'segmented'. Based on a generalized linear regression model (GLM), the 'segmented' package tries to estimate a new model having broken-line relationships for an (equivalent) temperature. A GLM incorporating all variables used in the GAMs was fitted (R package 'mgcv' and 'splines') prior to the fitting of the breakpoint model. Initial values for the breakpoints were specified over a range of possible integer values as indicated by the (equivalent) temperature–mortality plots. Where no breakpoint was evident in the (equivalent) temperature-mortality plots, the slope was determined by a GLM.

6.3 RESULTS

6.3.1 The urban bioclimate in Bangladesh

Bangladesh is located between the 21st and the 26th degree of northern latitude. The Köppen-Geiger system classifies it as a tropical winter dry (monsoon) climate, characterized by constant high temperatures (all monthly average temperatures above 18°C) and a pronounced dry season (less than 60 mm precipitation in the driest month) (Kottek et al. 2006). Figure 6.1 shows the monthly distribution of temperature, TPIs and precipitation in Dhaka. Monthly average temperatures remained high from April to October with equivalent temperatures surpassing measured temperature by up to 15 Kelvin during this period. Differences between TPIs and measured temperature were less pronounced for the colder period between October and March. Highest differences between temperature and TPIs were observed for monthly average maximum values. The differences between average minimum temperatures and TPIs were rather small. Heavy rainfall occurred between June and September, and thermal levels remained high throughout this season (Figure 6.1).

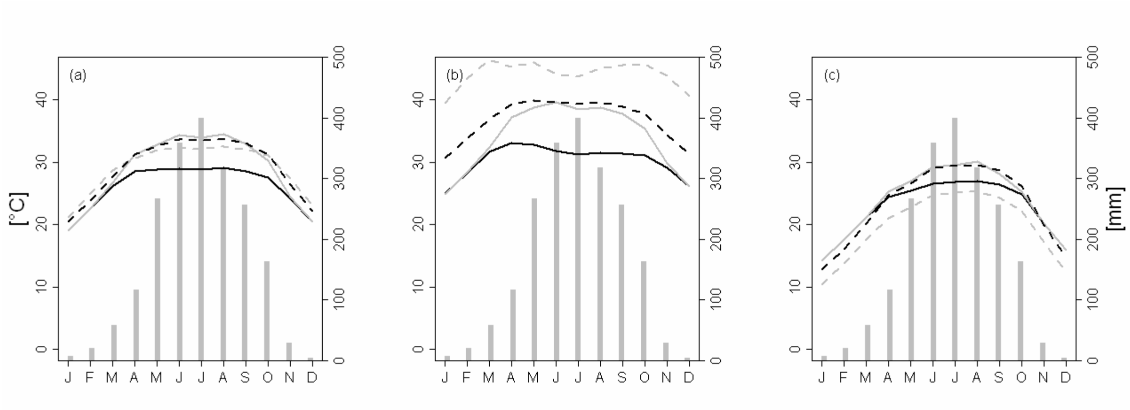

Figure 6.1: Distribution of temperature (black solid line), HI (gray solid line), PET (gray dashed line), and UTCI (black dashed line) of monthly average mean values (a), monthly average maximum values (b), and monthly average minimum values (c). Monthly rainfall in mm

Urban-rural differences in temperature ranged between 0.3 and 2.1 K. The most pronounced UHI was observed in March and April during the dry summer season, whereas its magnitude was reduced during the rainy (monsoon) season (Figure 6.2). In addition to higher temperatures, lower specific or relative humidity and reduced wind speed were measured at the urban station (data not shown). Differences in TPIs basically followed the seasonal distribution of temperature differences, but the magnitude of equivalent temperature differences varied heavily, depending on the index considered. Although the UHI has often been described as a night-time phenomenon (Memon et al. 2008), this could not be observed in this study. Urban-rural differences in minimum (night-time) temperatures were rather smaller. A more detailed analysis of bioclimate and thermal stress in Dhaka and Bangladesh has been presented elsewhere (Burkart and Endlicher 2011).

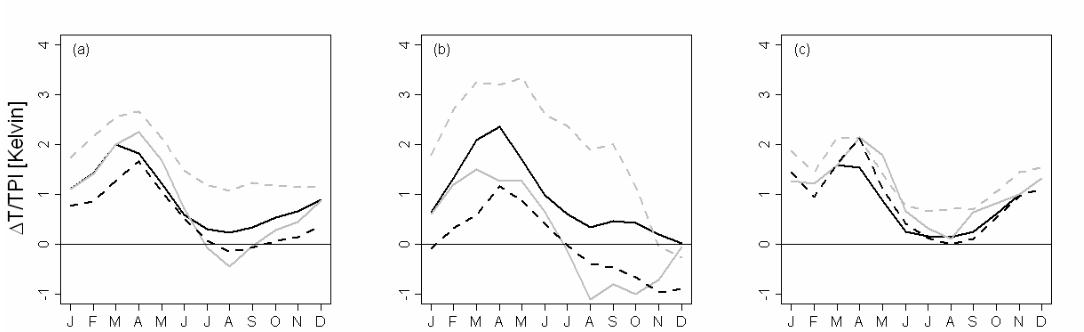

Figure 6.2: Seasonal distribution of urban–rural (equivalent) temperature differences between Dhaka and Mymensingh for monthly average mean values (a), monthly average maximum values (b), and monthly average minimum values (c)

6.3.2 Deaths and mortality

Major causes of death included respiratory, cardiovascular and infectious diseases, which accounted for almost half of all deaths. Crude death rates as well as age-adjusted mortality rates differed between urban and rural areas (Table 6.1). Generally, the crude death rate was higher in rural areas while the age-adjusted mortality was higher in urban areas. Concerning communicable disease mortality (infectious, respiratory and diarrhoeal, vector-borne diseases) crude death and age-adjusted mortality rates were higher in rural areas. On the contrary, non-communicable disease mortality was higher in urban areas. Death counts were unevenly distributed during the study period with some kind of seasonal pattern emerging. During the cold season generally a higher number of deaths was registered with corresponding lower numbers during the warmer season. Time-series plots of death counts from January 2003 to December 2007 for deaths due to all-causes and cardiovascular disease are provided in the Supplementary Material (Appendix 2, Figure A2.1 and A2.2).

Table 6.1: Crude death rates and age-adjusted death rates per 1,000 population by cause of death

Cause of death	Crude death rate		Age-adjusted mortality rates	
	Rural	Urban	Rural	Urban
All causes	5.78	5.36	8.27	9.91
Respiratory disease	1.12	0.87	1.44	1.32
Cardiovascular disease	0.67	1.11	1.06	2.11
Diarrhoeal disease	0.23	0.15	0.26	0.24
Infectious disease	0.72	0.47	0.84	0.69
Cancer	0.36	0.40	0.53	0.68
Vector borne disease	0.09	0.04	0.11	0.09
Malnutrition	0.12	0.10	0.13	0.15
Others	2.49	2.23	3.91	4.62

6.3.3 Thermal effects on mortality

This study demonstrated a clear association between thermal conditions and mortality. Both, cold and heat effects could be observed. Figure 6.3 and 6.4 show smoothed exposure-response relationships between all-cause and cardiovascular mortality and the mean (equivalent) temperatures for different lag periods. Differences in the shape of the temperature-mortality curve and the equivalent temperature-mortality curves were rather small. Similar to many other studies, we focused on the effect of mean temperatures, which permitted better comparability with other studies. Additionally, we assessed effects of minimum and maximum values. Exposure-response plots were included in the Supplementary Material (Appendix 2, Figures A2.3 to A2.6).

In terms of all-cause mortality, a '*V*'-shaped (equivalent) temperature-mortality relationship could be observed (Figure 6.3). The increase in mortality was roughly linear above and below a breakpoint (equivalent) temperature. For all lag periods and indices an increase in mortality with decreasing temperatures (cold effect) was observed. Mortality increased by approximately 1-3% per 1°C decrease in (equivalent) temperature in urban and rural areas (Table 6.2; Appendix 2, Tables A2.2 and A2.3). Above a specific threshold an increase in mortality with increasing temperature (heat effect) was observed for some models. Heat effects proved to be more divers, varying between areas and lag period. While in urban areas an increase in all-cause mortality was observed for all lag periods, in rural areas a heat effect was only observed for lag periods of 0-1 and 0-6 days. Considering minimum (equivalent) temperature, heat effects were less pronounced and mostly evident for a lag period of 0-1 days. Maximum temperatures, however, exhibited a heat effect on all-cause mortality in urban and rural areas for all lags (but not for PET). The percentage increase in rural mortality for a 1°C increase in (equivalent) temperature ranged between 0.5 and 6%. In urban areas the percentage increase in mortality was generally higher and amounted up to 15% per 1°C increase in (equivalent) temperature (Table 6.2; Appendix 2, Tables A2.2 and A2.3). Breakpoint mean temperatures ranged between 28 and 29°C in rural and urban areas with no considerable difference between the two categories. Threshold equivalent temperatures were surpassing threshold temperatures. Again, rural and urban areas exhibited no major differences in this respect.

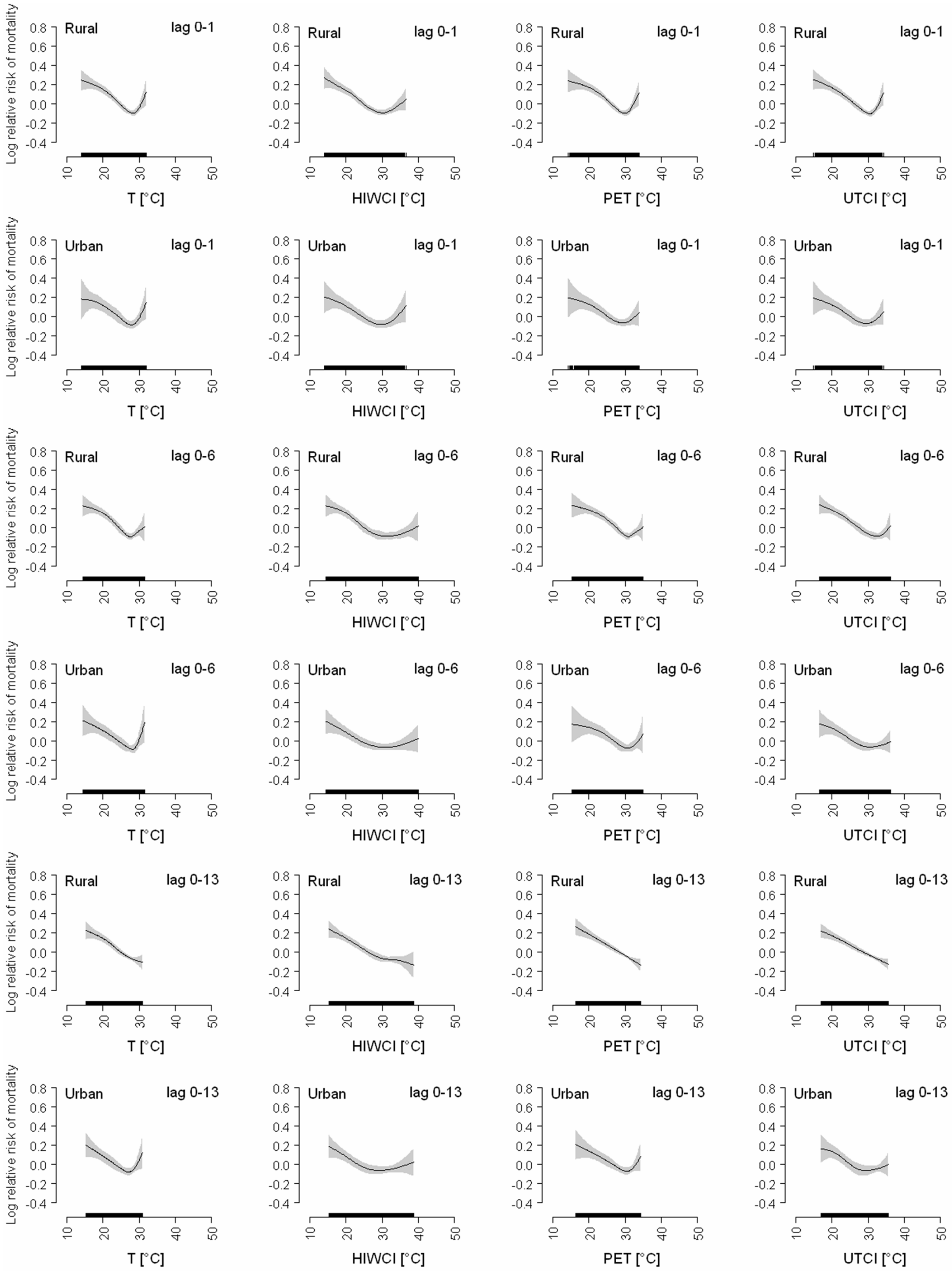

Figure 6.3: Regression curves for daily <u>all-cause mortality</u> on the mean (equivalent) temperatures over the current and previous day (lag 0-1), the current and 6 previous days (lag 0-6), and the current and 13 previous days (lag 0-13). Curves are adjusted for trend, season, day of the month and age. The variable to which the plot applies (temperature or TPI) is displayed as a rug plot at the foot of each plot. The 95%-confidence intervals are displayed by the shaded area

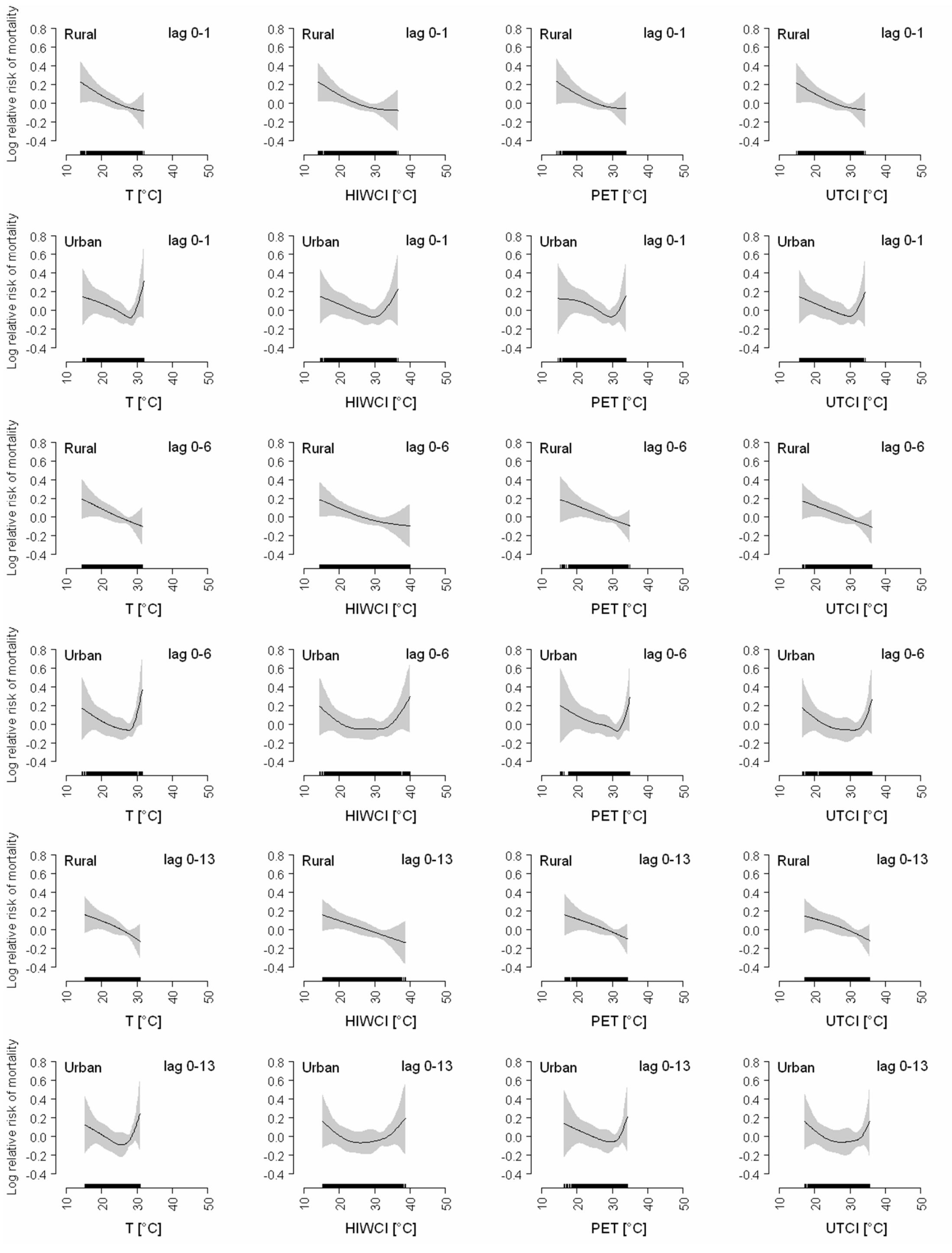

Figure 6.4: Regression curves for daily <u>cardiovascular mortality</u> on the <u>mean</u> (equivalent) temperatures over the current and previous day (lag 0-1), the current and 6 previous days (lag 0-6), and the current and 13 previous days (lag 0-13). Curves are adjusted for trend, season, and day of the month. The variable to which the plot applies (temperature or TPI) is displayed as a rug plot at the foot of each plot. The 95%-confidence intervals are displayed by the shaded area

A heat effect on cardiovascular mortality was solely observed in urban areas while in rural areas a decrease in mortality with decreasing (equivalent) temperatures was observed over the whole range of values (Figure 6.4). In urban areas mean (equivalent) temperatures exhibited the strongest heat effect, rising up to 15% mortality increase. The effect of maximum temperatures was slightly less strong and minimum temperatures featured a clearly smaller effect (Table 6.3; Appendix 2, Tables A2.4 and A2.5). However, the mortality increase varied heavily with TPI and lag periods and the confidence intervals predicted for the percentage increase in mortality were rather wide. Breakpoint (equivalent) temperatures were about the same as observed for all-cause mortality. Concerning cold effects, rural cardiovascular mortality increased by approximately 1% per 1°C decrease in (equivalent) temperatures. In urban areas, cold effects were slightly weaker, not exceeding 1% mortality increase per 1°C decrease in (equivalent) temperatures (Table 6.3; Appendix 2, Tables A2.4 and A2.5).

Table 6.2: Thresholds and slopes of the mean (equivalent) temperature–all-cause mortality relationship in rural and urban areas for different lag periods

	Rural			Urban		
	Threshold [°C]	Cold effects [a]	Heat effects [b]	Threshold [°C]	Cold effects [a]	Heat effects [b]
Temp. [c]						
Lag 0-1	28.9 (+/-0.6)	2.8 (+/-0.6)	4.4 (+/-5.4)	29.4 (+/-0.6)	2.4 (+/-0.9)	13.7 (+/-10.9)
Lag 0-6	28.1 (+/-1.0)	3.0 (+/-0.7)	1.5 (+/-3.7)	28.8 (+/-0.9)	2.4 (+/-0.9)	7.5 (+/-9.6)
Lag 0-13	–	2.6 (+/-0.6)	–	24.0 (+/-6.1)	3.3 (+/-1.8)	1.5 (+/-3.1)
HI [d]						
Lag 0-1	30.7 (+/- 1.1)	2.5 (+/-0.5)	2.4 (+/-2.9)	31.2 (+/-1.3)	2.2 (+/-0.9)	3.9 (+/-4.1)
Lag 0-6	31.6 (+/- 2.1)	2.4 (+/-0.5)	0.6 (+/-1.4)	29.3 (+/-4.6)	2.4 (+/-1.0)	0.7 (+/-1.8)
Lag 0-13	–	2.6 (+/-0.6)	–	25.0 (+/-6.0)	2.9 (+/-1.8)	0.8 (+/-1.4)
PET [e]						
Lag 0-1	30.5 (+/-0.7)	2.6 (+/-0.6)	5.7 (+/-5.5)	30.9 (+/-0.7)	2.1 (+/-0.9)	10.9 (+/-9.2)
Lag 0-6	31.8 (+/-0.8)	2.5 (+/-0.6)	2.9 (+/-4.4)	32.3 (+/-1.0)	1.9 (+/-0.9)	8.9 (+/-9.3)
Lag 0-13	–	2.6 (+/-0.6)	–	31.2 (+/-2.1)	2.1 (+/-1.0)	2.8 (+/-5.8)
UTCI [f]						
Lag 0-1	31.5 (+/-0.5)	2.5 (+/-0.5)	6.3 (+/-5.6)	31.3 (+/-0.8)	2.1 (+/-0.9)	8.0 (+/-8.3)
Lag 0-6	32.8 (+/-1.2)	2.4 (+/-0.5)	0.4 (+/-4.1)	32.7 (+/-2.1)	1.9 (+/-0.9)	2.3 (+/-5.0)
Lag 0-13	–	2.6 (+/-0.6)	–	31.0 (+/-5.3)	2.3 (+/-1.0)	0.5 (+/-4.7)

[a] Percentage increase in mortality for each °C decrease in (equivalent) temperature below threshold (95% CI)
[b] Percentage increase in mortality for each °C increase in (equivalent) temperature above threshold (95% CI)
[c] Temperature
[d] Heat Index/Wind Chill Index
[e] Physiological Equivalent Temperature
[f] Universal Thermal Climate Index

Table 6.3: Thresholds and slopes of the mean (equivalent) temperature–cardiovascular mortality relationship in rural and urban areas for different lag periods

	Rural			Urban		
	Threshold [°C]	Cold effects [a]	Heat effects [b]	Threshold [°C]	Cold effects [a]	Heat effects [b]
Temp. [c]						
Lag 0-1	–	1.1 (+/-1.6)	–	29.1 (+/-1.8)	1.0 (+/-2.0)	8.3 (+/-20.9)
Lag 0-6	–	1.2 (+/-1.6)	–	29.1 (+/-1.2)	0.7 (+/-2.0)	12.7 (+/-18.9)
Lag 0-13	–	1.1 (+/-1.6)	–	28.3 (+/-1.8)	0.7 (+/-2.1)	9.2 (+/-16.5)
HI [d]						
Lag 0-1	–	1.1 (+/-1.6)	–	32.1 (+/-3.2)	0.7 (+/-1.7)	4.0 (+/-12.0)
Lag 0-6	–	1.2 (+/-1.6)	–	34.4 (+/-3.8)	0.4 (+/-1.4)	3.4 (+/- 8.9)
Lag 0-13	–	1.1 (+/-1.6)	–	31.1 (+/-9.9)	0.6 (+/-1.9)	2.1 (+/- 5.1)
PET [e]						
Lag 0-1	–	1.1 (+/-1.6)	–	30.7 (+/-2.0)	1.0 (+/-1.9)	7.9 (+/-16.4)
Lag 0-6	–	1.2 (+/-1.6)	–	32.5 (+/-1.4)	0.7 (+/-1.8)	15.5 (+/-20.7)
Lag 0-13	–	1.1 (+/-1.6)	–	31.5 (+/-2.4)	0.6 (+/-1.9)	7.7 (+/-15.5)
UTCI [f]						
Lag 0-1	–	1.1 (+/-1.6)	–	31.4 (+/- 2.0)	0.8 (+/-1.8)	6.5 (+/-17.2)
Lag 0-6	–	1.2 (+/-1.6)	–	33.9 (+/- 1.7)	0.4 (+/-1.6)	9.2 (+/-21.7)
Lag 0-13	–	1.1 (+/-1.6)	–	29.8 (+/-16.8)	1.0 (+/-3.5)	1.9 (+/-5.0)

[a] Percentage increase in mortality for each °C decrease in (equivalent) temperature below threshold (95% CI)
[b] Percentage increase in mortality for each °C increase in (equivalent) temperature above threshold (95% CI)
[c] Temperature
[d] Heat Index/Wind Chill Index
[e] Physiological Equivalent Temperature
[f] Universal Thermal Climate Index

6.3.3.1 *Predictive advantage*

Judging by the (minimization) of the UBRE criterion, minimum values of temperature and TPIs showed a slight predictive advantage in rural areas whereas maximum values of temperature and TPIs had a higher predictive advantage in urban areas. In the case of all-cause mortality, mean, maximum and minimum values had about the same predictive power. For cardiovascular mortality minimum and maximum values seemed to be advantageous. Comparing the predictive power of temperature and TPIs in the 12 different models, temperature produced the best results in six models and HI and PET each had the highest predictive advantage in one model. The UTCI was strongest in four models (Appendix 2, Table A2.1). Nevertheless, differences were only minor.

6.4 DISCUSSION

6.4.1 General findings and conclusions

This study observed an increase in mortality at both, low and high temperatures. Generally, the Bangladeshi populations seemed to be well adapted to high temperatures with a negative association between temperature and mortality over a wide range of temperature values. Nevertheless, adverse effects of heat emerged above a specific threshold (equivalent) temperature. Heat effects depended on the cause of death, location (urban vs. rural), and lag period. Urban areas generally exhibited stronger and longer-lasting heat effects. Heat effects in urban areas exerted influence up to three weeks (lag 0-13) whilst in rural areas heat effect subsided after one week (lag 0-6). Concerning cardiovascular mortality, no heat effect was found in rural areas whereas urban areas were facing remarkable excess mortality for all lag periods and indices. The mortality increase due to elevated temperature observed in this study (~7-14%) was more pronounced than the effect observed for other low-latitude cities like Delhi (3.9%), Bangkok (5.8%) or São Paulo (3.5%) (McMichael et al. 2008). However, judging by the width of the confidence intervals, slope estimation is rather imprecise; most likely due to the small number of observations above the thresholds. Still, these findings seem to suggest that heat effects are associated with severe excess mortality, and that heat effects are stronger than cold effects.

Despite the tropical climate and the elevated temperatures characteristic to this region, some sort of cold effect was observed. Other studies conducted in Delhi (India), Bangkok (Thailand) and Salvador (Brazil), or Matlab (a rural area in Bangladesh) found no cold effect until a lag period of 0-13 days (Hashizume et al. 2007; McMichael et al. 2008). The percentage increase of all-cause mortality per 1°C (equivalent) temperature recorded in this study ranged between 1% and 3%. The slopes determined are comparable with those found for a lag period of 0-13 days in Delhi (2.8%), Bangkok (4.1%), or São Paulo (2.5%) (McMichael et al. 2008). More shallow slopes were observed for mid-latitude cities like Ljubljana (0.4%), Bucharest (0.9%), or Sofia (0.9%) (McMichael et al. 2008).

When assessing thermal effects on mortality, adaptation plays a crucial role. Adaptation involves physiological, cultural and behavioral factors. Physiological adaptation relates to the time spent living in an area (long-term adaptation), but also to the thermal conditions prevalent in the previous weeks and months (short-term adaptation). Cultural and behavioral strategies refer to building structures, clothing, outdoor activities etc. Generally, temperature effects, and particularly heat effects observed in this study were strongly pronounced; most likely as adaptation is insufficient due to the low socio-economic status of the overriding majority of the Bangladeshi population.

A central research question certainly is whether urban populations are more vulnerable to heat as they are more exposed (due to the UHI), or whether urban populations are more susceptible to heat as a consequence of a modified health or age pattern. A lack in physical activity, sedentary lifestyle and unhealthy food habits have been named as factors contributing to a higher prevalence of non-communicable diseases in urban areas (Proctor et al. 1996; Shetty 2002; Kelishadi et al. 2008; Khan et al. 2009). Looking at threshold temperatures for all-cause mortality, no major differences were observed between urban and rural areas. For interpreting this observation one must understand that the temperatures used in this analysis are macro-climatic values, meaning that the effective temperatures prevailing in urban areas are most likely higher. Equal threshold temperatures would therefore rather indicate that the effects of urban excess temperatures are compensated, e.g. by better adaptation. Nevertheless, the mortality increase in urban areas determined by the breakpoint models exceeded the mortality increase in rural areas. Moreover, a pronounced heat effect on cardiovascular mortality was found in urban areas while rural areas exhibited no effect. Whether urban populations are more vulnerable or more susceptible cannot be answered at that point; most likely a combination of both can be assumed.

While the importance of minimum temperatures for the regeneration of the human organism during heat periods has been suggested, minimum values solely exerted moderate heat effects in this study. Instead, maximum and mean temperatures exhibited pronounced heat effects suggesting that constant exposure to high temperature or exposure to very high temperatures for a restricted time-frame causes adverse effects on health. Considering their predictive advantage, minimum and maximum values showed to be slightly advantageous. For TPIs, no predictive advantage was observed. Nevertheless, the physical mechanisms triggered by humidity, air movement or radiation are indisputable. The crucial question is the extent to which human health outcomes are connected to the human heat balance. In addition to the effect of meteorological conditions on the prevalence of certain pathogens, biochemical reactions triggered by temperature have an effect on health outcomes. Several studies have demonstrated that changes in blood composition are influenced by temperature.

Exposure to cold can lead to an increase in blood and plasma viscosity as well as raised red blood cells (Keatinge et al. 1984; Keatinge et al. 1986). Moreover, cholesterol, fibrinogen, C-reactive protein and Interleukin-6 increase with decreasing temperatures (Schneider et al. 2008). Induced haemoconcentration can result in arterial thrombosis or other cold-induced cardiovascular reflexes (Keatinge et al. 1984; Neild et al. 1994; Keatinge and Donaldson 1995). Furthermore, there is evidence that cold causes physiological changes in cellular and humoral immunity or more directly, can affect the respiratory tract, for example through bronchoconstriction (Bull 1980; Berk et al. 1987). Following exposure to heat, reduced plasma and platelet volume could be observed with increases in blood viscosity. Augmented plasma protein and cholesterol levels and higher red blood cell and platelet counts were also detected (van Beaumont et al. 1974; van Beaumont et al. 1981). These changes are likely to cause coronary and cerebral thrombosis during hot weather finally resulting in cardiovascular-related death (Keatinge et al. 1986).

These biochemical processes are accorded no consideration by (current) thermo-physiological models. However, they may well constitute tipping points in the cardiovascular system, beyond which a breakdown occurs. Moreover, indices are usually determined for a standardized individual of middle-age and average height and weight. However, those in danger of dying from heat or cold are most likely to be of an older or younger age, or to suffer from a medical condition (e.g., obesity, hypertonia, diabetes). Incorporating these factors into thermo-physiological models may well improve the prediction of mortality. The relevance and potential of TPIs should be explored in future research.

6.4.2 Strengths and limitations

Few studies have explored thermal effects on mortality in tropical countries and this study represents a substantial contribution to a much-improved understanding of the relationship between atmospheric conditions and mortality in these regions. The analysis is based on continuous data from a sample covering Bangladesh on a nationwide level. In the context of a developing country such data availability is rather exceptional. The practice of surveying households instead of merely collating registered fatalities reduces the risk of underreporting. Moreover, the dual recording system brings quite reliable data. Most importantly, this study not only considered the effect of temperature, but also the combined effect of temperature and other meteorological parameters. Nevertheless, some limitations remain. Reduced data availability made it impossible to account for regional or location-specific climatological and meteorological variations. In the absence of long-term air pollution data air pollution effects could not be incorporated in the analysis. Variations were to some extend only accounted for by seasonal adjustment. While we attribute a quite high reliability to all-cause mortality, the classification of cardiovascular deaths is likely to be subject to error. Cardiovascular death was mostly advanced if a subject was suffering from hypertonia thus suggesting that some sort of cardiovascular malfunction was to some extent adding to death. However, no medical certification or autopsy underlies the classification. Moreover, our study illustrated the general association between thermal conditions and human mortality without allowing conclusions about extreme events such as heat or cold waves. The nature of our data (a sample covering approximately 1% of the population) meant that we were unable to cover such excess mortalities. Nevertheless, it is highly likely that following an extreme event, mortality could increase with a steeper gradient than shown for this study.

6.5 CONCLUSIONS

Temperature effects were strongly pronounced in Bangladesh surpassing levels observed for other low-latitude areas. We assume that socio-economic conditions are responsible for the strongly pronounced impact of weather effects. Although a cold effect occurred over a wide range of temperature values, a steep increase in heat-related mortality was observed above a threshold. In particular, urban populations seemed to be at high risk of heat-related mortality. Urban excess temperatures or a higher susceptibility of urban populations might both contribute to this increased risk. These adverse heat effects may well increase with continuing urbanization and the intensification of excess temperatures due to the densification of building structures. A climate change-induced rise in temperature could also represent an aggravating factor for which coping strategies are urgently required.

ACKNOWLEDGEMENTS

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CHAPTER 7: AGE-SPECIFIC ANALYSIS OF SHORT- AND LONG-TERM METEOROLOGICAL EFFECTS ON MORTALITY IN BANGLADESH

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ABSTRACT

Meteorological conditions have been shown to cause short- and long-term variations in mortality. The nature and magnitude of these effects depend on environmental framework conditions and other non-atmospheric variables. Within the scope of this study, we assessed whether and to what extent the atmosphere-mortality relationship in Bangladesh is influenced by age. Daily death count data were stratified into four different age groups. Various Poisson regression models were fitted to investigate meteorological effects ranging from a few days to several weeks and months. Models were adjusted for trend and day of month and partly for season. Breakpoints constituting a reversion in the relationship between (equivalent) temperature and mortality were determined, and the increase in mortality above and below these threshold temperatures was estimated. While child and youth mortality peaked during the summer and post-monsoon season and showed a rather weak association with temperature, adults and the elderly exhibited quite marked cold and heat effects with highest mortality during the winter. Strongly pronounced heat effects were found for the elderly.

7.1 INTRODUCTION

To date, a multitude of studies have assessed the short- and long-term effects of meteorological or atmospheric conditions on human mortality (Basu and Samet 2002; Basu 2009). In industrialised countries of the mid-latitudes, mortality rates generally peak during the cold winter season and increase with decreasing temperatures (ibid). Although the lowest levels of mortality are usually observed during summer, extreme events (i.e., heat waves) can lead to tremendous excess temperature as observed during the European summer heat waves of 2003 or the Chicago heat wave of 1995 (Schär and Jendritzky 2004; Kaiser et al. 2007; Robine et al. 2007). With the projected consequences of climate change, researchon the nature of atmospheric effects has regained relevance with the intent to target adaptation and mitigation measures most effectively. Given the restricted data availability, thus far, few of these studies have focused on tropical developing countries. However, considering the high prevailing temperatures in these regions and the generally low socio-economic status, developing countries might be most vulnerable to a rise in temperature.

In two recent studies, seasonal and thermal effects on mortality in Bangladesh were investigated (Burkart et al. 2011a; Burkart et al. 2011b). As in countries with temperate climates and a high socio-economic status, excess mortality was associated with the cold season and with low temperatures. Nevertheless, for several strata and particularly for urban areas, a pronounced increase in mortality with rising temperatures (i.e., a heat effect) was found. Although a detailed cause- and location-specific analysis was conducted, the limited number of observations did not allow a further stratification by age. However, we hypothesise that the shape and magnitude of seasonal or thermal effects vary with different age groups and underlying disease profiles. In particular, children and the elderly merit a more thorough investigation given the high mortality rates in both age groups. The objective of the present study was to conduct an age-specific analysis of short- and long-term meteorological effects, thus complementing the preceding research outlined above. To allow for age stratifications, other strata were left unconsidered.

7.2 METHODS

7.2.1 Meteorological data and thermo-physiological modelling

Meteorological data for 26 stations distributed over Bangladesh were provided from the Bangladesh Meteorological Department. The data comprised three-hourly values of temperature, humidity, wind speed, and cloud coverage. Based on these three-hourly values, the universal thermal climate index (UTCI) was modelled. The UTCI is based on the Fiala model (Fiala et al. 1999; Fiala et al. 2001), a thermo-physiological model, which has been extensively validated using experimental data from numerous groups (Jendritzky et al. 2007; Universal Thermal Climate Index 2010). The output variables of this model are equivalent temperatures, which are temperatures resulting in the same energy gain or loss a standard human would experience in a reference environment (with 50% relative humidity, still air, and a radiant temperature equalling air temperature). The input variables are temperature, humidity, wind speed, and mean radiant temperature. The input variable, mean radiant temperature (uniform temperature of a surrounding surface that results in the same radiation energy gain on a human body as the prevailing radiation fluxes), is modelled as a function of temperature and cloud coverage using RayMan (Version 1.2) (Matzarakis et al. 2007).

Daily mean values of temperature and the UTCI were calculated for each station as far as the measurements were complete for a given day. Approximately 17% of the daily calculated data were missing. Missing daily values of temperature or the UTCI were replaced by linear interpolation. Bangladesh was considered as representing one climate zone. This conclusion was based on the determination of the Kaiser criterion as well as a cluster analysis. For the 26 meteorological time-series, the Kaiser criterion indicated that one factor represents more than 99% of the variability. In a second step, we conducted a cluster analysis to investigate whether different large-scale regional climate units become apparent (e.g., North-South differences with higher temperatures in one region and lower in the other region). The cluster analysis did not reveal any macro-scale pattern. Therefore, any existing regional meteorological variations were not considered, and a spatial average daily mean value was calculated. Spatial (equivalent) temperature maps were generated for each day using inverse distance interpolation (R, Version 2.11.0, package 'gstat'). Subsequently, a mean value was calculated from the map grid values. The spatial aggregation helped to increase the statistical power and significance of the regression analysis but did not account for meso- or micro-scale specifications.

7.2.2 Mortality data

Mortality data analysed within this study were collected within the Sample Vital Registration System (SVRS), a core activity of the Bangladesh Bureau of Statistics (BBS). The SVRS comprises and surveys approximately 200,000 households with an average size of 4.7 members in rural and urban areas and in the statistical metropolitan area (SMA). A number of households (132,646) are located in rural areas, whereas 57,852 households are located in urban areas and 16,024 households placed in the SMA. The strength of the SVRS is the collection of data under a dual recording system. Events are recorded continuously by a local registrar when they occur on a redesigned questionnaire (system-1). In addition, events are registered retrospectively by officials from the Upazila division of the BBS on a quarterly basis using the same questionnaire as the local registrar (system-2). Afterwards, the two questionnaires obtained from system-1 and system-2 are matched by quality control personnel of the BBS. Partially-matched and non-matched events are subject to further verification through field visits. The following information is recorded: name of the deceased, date of birth, date of death, and sex of the deceased. Moreover, a cause of death is attributed; however, this is not medically certified.

For the purpose of this study, all accidental and maternity-related deaths were excluded. The sample was stratified into four age groups: children (1-4 years), youths (5-14 years), adults (15-64 years), and elderly (65+ years). Deaths of infants younger than one year were not included because births exhibit seasonal variations that could confound the analysis. Because severe flooding submerged major parts of the country in 2004, we conducted a sensitivity analysis running our analysis with and without data from this year. As results were mostly unaffected, the data from 2004 were included in this study. In total, 22,819 deaths were analysed. A total of 1,509 deaths were allotted to children, 1,047 to youths, 9,106 to adults and 11,157 to the elderly. In addition, we divided the sample between urban and rural areas to elaborate differences by location (data from the SMA were excluded). Of the deaths analysed, 6,226 occurred in urban areas and 15,409 in rural areas. In the age group of one to four years, 282 deaths occurred in urban and 1,126 in rural areas. In the age group of five to 14 years, 196 deaths occurred in urban and 783 in rural areas. In the age group of 15 to 64 years, 2,703 deaths occurred in urban and 5,860 in rural areas. In the age group of those 65 years and older, 3,045 deaths occurred in urban and 7,640 in rural areas.

7.2.3 Statistical analysis

Seasonal fluctuations of daily mortality counts and the association between (equivalent) temperature and daily mortality were modelled using Poisson generalised additive models (GAMs). Penalised regression splines were used to allow for nonlinear confounding effects. Smoothing parameters were chosen to minimise the Un-Biased Risk Estimator score for the models. A Bayesian approach to variance estimation was employed to estimate the confidence intervals (Wood 2006). The R (Version 2.11.0) package 'mgcv' was used for model fitting. For assessing seasonal variations in mortality, the day of the year was used as predictor variable adjusting for trend. For assessing more immediate thermal effects, temperature and the UTCI were used as predictors adjusting for trend and day of the month. In addition, a categorical dummy variable for seasonal adjustment was incorporated to remove the mid- to long-term seasonal cycles in the series, as we aimed at investigating short-term influences. Moreover, this dummy variable allowed for reflection of seasonal differences in air pollution levels with high levels during winter (stable atmospheric conditions) and decreasing levels in the pre-monsoon and monsoon seasons (labile atmospheric conditions). In Bangladesh, the years can be divided into three main seasons: the winter season (October to February), summer/pre-monsoon season (March to May), and the monsoon/rainy season (June to September). Considering the high correlation between humidity and temperature, humidity was not integrated separately into the models because this may result in multi-collinearity problems. Instead, humidity and other meteorological variables were accounted for by the UTCI. Models were fitted for three different lag periods to identify heat and cold effects caused by recent and more delayed thermal conditions. The average of daily (equivalent) temperatures and temperatures of the previous day (lag 0-1), the recent six days (lag 0-6) and the recent 13 days (lag 0-13) were incorporated in the models. Formulas for GAMs are provided in the supplementary Material (Appendix 3, Formulas A3.1 and A3.2).

To detect threshold temperatures and to quantify the effects of cold and heat, breakpoint models (hockey stick models) were applied. Such breakpoint models assume a piecewise linear relationship between the response and the explanatory variables, which are connected at the so-called breakpoints (Muggeo 2008). In this study, the breakpoints represent the temperatures above and below which the temperature–mortality relationship changes. Breakpoint models based on a generalised linear regression model (GLM) were fitted using R (Version 2.11.0) and the R package ‘segmented’. A GLM incorporating all variables used in the GAMs was fitted (R package ‘mgcv’ and ‘splines’) prior to the fitting of the breakpoint model. Initial values for the breakpoints were specified over a range of possible integer values as indicated by the (equivalent) temperature–mortality plots. Where no breakpoint was evident in the (equivalent) temperature-mortality plots, the slope was determined by a GLM.

For the regression modelling, death counts were aggregated over all locations and regions in Bangladesh. As outlined above, the regional aggregation of data is adequate for the purpose of this study, as Bangladesh can sufficiently be considered as one climatic zone with proximate and highly correlated meteorological value. However, as previous studies demonstrated elementary differences between urban and rural areas, a stratified analysis was conducted in addition, and models were fitted separately for deaths occurring in urban and rural areas. Due to the limited number of observations, outputs of these models often did not render significant results. For this reason, the focus of this study rests on the findings from the location-unspecific analysis. Nevertheless, model outputs of the stratified sample of urban and rural areas were included in the Supplementary Material (Appendix 3), and relevant findings were excerpted and addressed within the results and discussion sections.

7.3 RESULTS

7.3.1 Age-specific mortality rates

Mortality rates varied considerably over different age groups in Bangladesh (Table 7.1). For infants and children under five years, the most frequent causes of death were respiratory and infectious diseases. In addition, diarrhoeal diseases and malnutrition contributed considerably to mortality. Vector-borne and non-communicable diseases have no substantial share in this age group. For youths and adults, mortality rates are naturally lower than for children and the elderly. Major causes of death in youths are similar to those observed for children and infants with respiratory and infectious diseases being the main causes. For adults, respiratory and infectious diseases remain relevant, but cardiovascular and vector-borne diseases become more important in this age group. In the elderly, respiratory and cardiovascular diseases contribute the highest share to mortality; however, infectious and vector-borne diseases are also relevant. In the elderly age group, a great share of deaths are not classified specifically or categorised as “old age diseases”. In rural areas, the mortality rates are generally higher except for adults. In particular, respiratory, diarrhoeal, and infectious diseases as well as malnutrition are more prevalent causes of death in rural areas, whereas cardiovascular diseases are more dominant in urban areas (Appendix 3, Tables A3.1 and A3.2).

Table 7.1: Age-specific mortality rates per 100,000 in Bangladesh

	Infants and Children (0-4 yrs.)	Youths (5-14 yrs.)	Adults (15-64 yrs.)	Elderly (65+ yrs.)
Respiratory disease	390.8	13.0	42.5	763.5
Cardiovascular disease	11.9	4.5	75.0	766.0
Diarrhoeal disease	83.6	9.2	8.1	94.3
Infectious disease	257.7	19.5	26.4	377.5
Cancer	30.8	4.5	3.2	25.6
Vector-borne disease	5.1	5.7	40.9	243.6
Malnutrition	70.2	3.2	2.7	25.6
Others	260.0	30.4	109.2	3303.3

7.3.2 Seasonal fluctuations by age group

The seasonal pattern of all-cause mortality varied heavily between different age groups (Figure 7.1). The most profound differences were found between those younger than 15 years and older than 15 years. Children and youths exhibited a bimodal pattern with the first maximum occurring in summer and the pre-monsoon season (April to June) and the second occurring at the end of the monsoon season and the beginning of winter (September to December). For children aged one to four years, the two annual peaks are equally strongly pronounced, but for older children and youths aged five to 15 years, the post-monsoonal peak became quite pronounced. For adults and the elderly, the seasonal pattern presents itself quite differently. For both age groups, mortality is highest during the cold winter months from December to February. Lowest mortality is observed during the monsoon season in August. In general, the seasonal amplitude is higher for adults and elderly than for children and youths and highest in those above the age of 65. The seasonal variations in urban versus rural areas corresponds largely with the pattern observed for the data aggregated over both areas (Appendix 3, Figures A3.1 and A3.2). However, for children and youths, no significant seasonal fluctuations could be found; this finding is most likely due to the reduced number of observations when stratifying the sample between urban and rural areas. For adults and the elderly, no major differences were observed between urban and rural areas with one notable exception: in the elderly age group, a marked secondary maximum in the summer and pre-monsoon season emerged in urban areas.

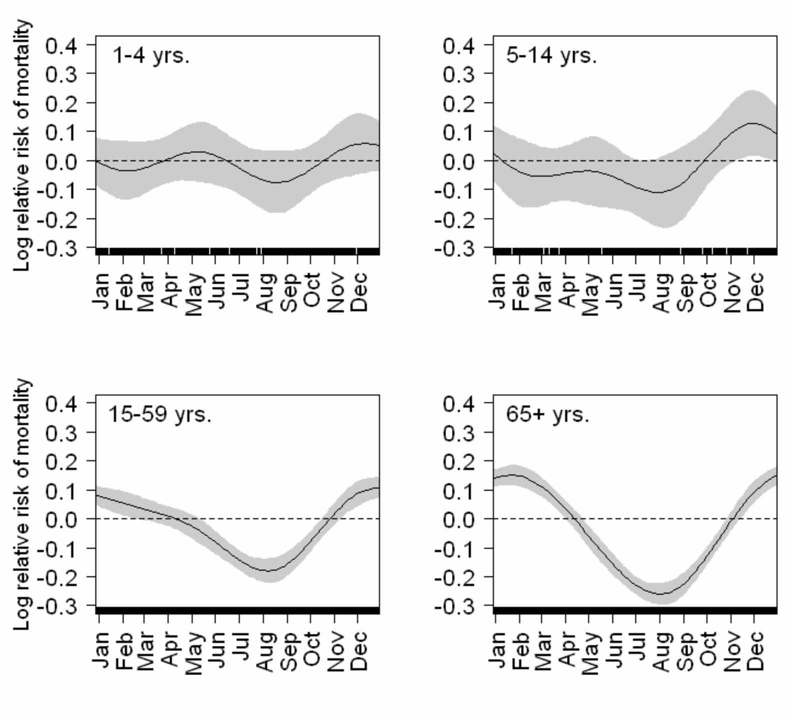

Figure 7.1: Seasonal variations of all-cause mortality in four different age groups. The frequency of observations is indicated by the rug plot on the foot of each diagram. The 95%-confidence intervals are displayed by the shaded area

7.3.3 Thermal effects by age group

Figures 7.2 and 7.3 show GAM model outputs; the plots illustrate the relationship between temperature and mortality and the UTCI and mortality, respectively. Few differences between the shape of the temperature-mortality and the shape of the UTCI-mortality relationship were observed. In the majority of the models, the UTCI had a small but not substantial predictive advantage. Generally, a rather weak association between (equivalent) temperature and mortality was observed for children and youths. The relationship was slightly positive denoting an increase in mortality with an increase in (equivalent) temperature over the whole range of values. However, given the small association and the limited number of observations, the results were not statistically significant. For adults and elderly, quite significant cold and heat effects emerged. Over a wide range of (equivalent) temperatures, a negative association between thermal levels and mortality existed; thus, mortality increased with decreasing temperature (i.e., a cold effect). This increase in mortality ranged around 3% per 1°C decrease in (equivalent) temperature for both age groups (adults and the elderly) and all analysed lag periods (Table 7.2).

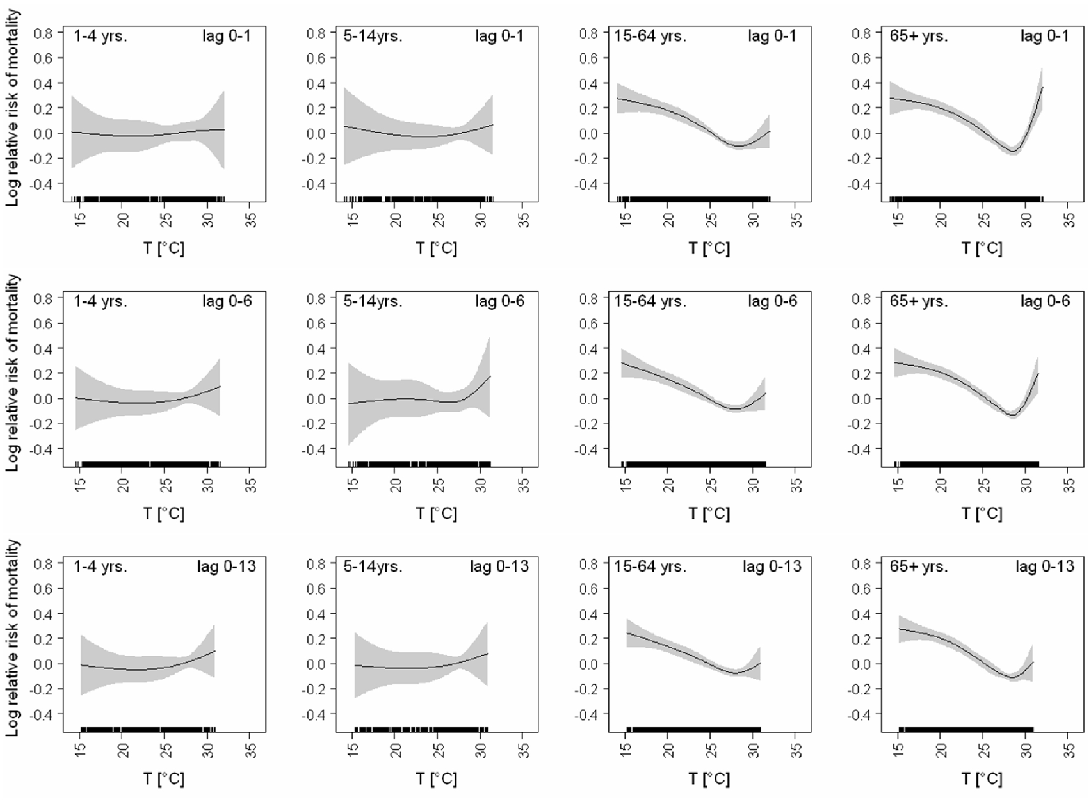

Figure 7.2: Regression curves for daily all-cause mortality on the mean temperatures over several lag periods and for different age groups. Curves are adjusted for trend, season, and day of the month. The frequency of observations is indicated by the rug plot on the foot of each diagram. The 95%-confidence intervals are displayed by the shaded area

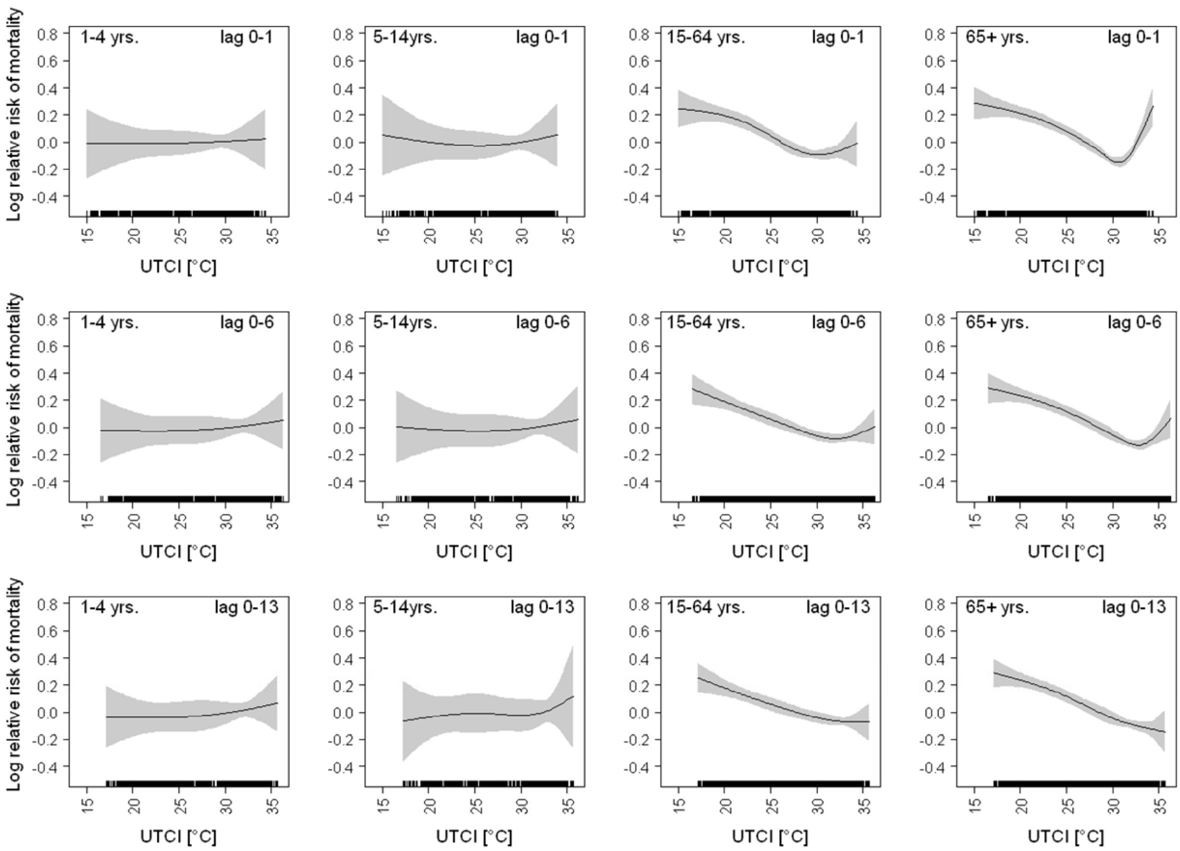

Figure 7.3: Regression curves for daily all-cause mortality on the mean universal thermal climate index (UTCI) over several lag periods and for different age groups. The curves are adjusted for trend, season, and day of the month. The frequency of observations is indicated by the rug plot on the foot of each diagram. The 95%-confidence intervals are displayed by the shaded area

At approximately the 90^{th} percentile of temperature and UTCI distribution, the (equivalent) temperature-mortality relationship reversed, and mortality started to increase with increasing temperature. The magnitude of this so-called heat effect varied by age and lag period. In general, adults between the ages of 15 and 64 years exhibited rather moderate heat effects. The mortality increase per 1°C increase did not exceed 2% (Table 7.2). However, for the elderly age group, heat effects became quite pronounced. These adverse heat effects were observed up to 7 days and caused an increase in mortality of almost 20% per 1°C (equivalent) temperature increase (Table 7.2). While cold effects persisted over several weeks, the effect of heat subsided after one week. Some differences concerning the intensity and shape of thermal effects were found between urban and rural areas (Appendix 3, Figures A3.3, A3.4, A3.5, and A3.6). While in rural areas practically no association between (equivalent) temperature and mortality was observed for children under five years, a slight increase in mortality ranging around 0.5% per 1°C was found over the whole range of values in urban areas. Contrary to that, for children and youths, a cold effect over the whole temperature range was found in urban areas, while rural areas exhibited a heat effect as observed for the aggregated data. However, judging by the width of the confidence intervals, these findings need to be considered carefully. For adults, no major differences were found between the urban and rural areas, whereas for the elderly, the magnitude of thermal effects differed significantly between the two areas. The observed cold effects were about 1% stronger in rural areas, whereas heat effects in urban areas exceeded those observed in rural areas many times over and additionally persisted over a longer time period. In urban areas, the increase in mortality came up to 20%, whereas in rural areas, the heat effects did not exceed 6% (Appendix 3, Table A3.3 and A3.4).

Table 7.2: Thresholds and slopes of the mean temperature/universal thermal climate index (UTCI)–all-cause mortality relationship for different lag periods

	Children (1-4 yrs.)			Youths (5-14 yrs.)			Adults (15-64 yrs.)			Elderly (65+ yrs.)		
	Threshold [℃]	Cold effect [a]	Heat effect [b]	Threshold [℃]	Cold effect [a]	Heat effect [b]	Threshold [℃]	Cold effect [a]	Heat effect [b]	Threshold [℃]	Cold effect [a]	Heat effect [b]
Temp.[c]												
Lag 0-1	-	-	0.2 (+/-1.8)	-	-	0.0 (+/-2.1)	28.1 (+/-1.2)	3.0 (+/-0.8)	1.6 (+/-4.7)	29.0 (+/-0.4)	3.6 (+/-0.7)	11.5 (+/-6.7)
Lag 0-6	-	-	0.5 (+/-1.9)	-	-	0.3 (+/-2.2)	27.7 (+/-1.5)	3.0 (+/-0.9)	1.7 (+/-4.3)	31.0 (+/-0.1)	3.4 (+/-0.7)	16.2 (+/-5.4)
Lag 0-13	-	-	0.7 (+/-1.9)	-	-	0.4 (+/-2.2)	-	3.1 (+/-1.1)	-	-	3.2 (+/-1.2)	-
UTCI [d]												
Lag 0-1	-	-	0.2 (+/-1.6)	-	-	-0.1 (+/-2.0)	30.3 (+/-1.3)	2.7 (+/-0.8)	1.5 (+/-4.1)	31.8 (+/-0.4)	3.1 (+/-0.6)	18.6 (+/-8.5)
Lag 0-6	-	-	0.3 (+/-1.5)	-	-	0.1 (+/-1.8)	31.8 (+/-2.3)	2.5 (+/-0.8)	0.9 (+/-3.3)	31.0 (+/-0.7)	2.8 (+/-0.6)	15.3 (+/-16.8)
Lag 0-13	-	-	0.5 (+/-1.5)	-	-	0.3 (+/-1.8)	-	1.8 (+/-0.6)	-	-	3.4 (+/-0.7)	-

[a] Percentage increase in mortality for each ℃ decrea se in (equivalent) temperature below threshold (95% CI)
[b] Percentage increase in mortality for each ℃ incre ase in (equivalent) temperature above threshold (95% CI)
[c] Temperature
[d] Universal Thermal Climate Index

7.4 DISCUSSION

This study demonstrated the importance of age when assessing the effects and consequences of meteorological conditions on mortality. In general, two different atmosphere-mortality regimes were found: the first for children and youths under the age of 15 years and the second for adults and elderly above the age of 15 years. Children and youths exhibited a bimodal seasonal pattern with one peak during the summer and early monsoon season and a second peak at the end of the monsoon and beginning of the winter season. The temperature-mortality analysis revealed a constant but small increase in mortality with increasing temperature over the whole range of values. On the contrary, seasonal variations exhibited by adults and the elderly were unimodal with a peak during the cold winter season and a trough during the warm summer and monsoon seasons. The analysis of short-term thermal effects revealed a 'V'-shaped (equivalent) temperature-mortality with increasing mortality at both low and high temperatures. While the cold-related mortality increase was equally strong for adults and the elderly, heat-related mortality was increased for those above the age of 65 years. We hypothesise that the age-dependent response towards thermal effects is caused by the varying disease and cause of death profiles between different age groups.

In children and youth, respiratory, diarrhoeal or other infectious diseases are quite prevalent and contribute to the major causes of death. Hence, the atmosphere-mortality relationship in these age groups is dominated by the effects that meteorological conditions exercise on the agents provoking such diseases. Both thermal and hydrological conditions are critical for the replication and survival of pathogens. The ability of bacteria to thrive in hot and humid conditions provides a good explanation for the mortality peak during the summer and pre-monsoon season and for the general positive association between temperature and mortality. In addition, the onset of heavy rainfall at the beginning of the monsoon season is likely to cause a high surcharge of water supply and strain on the sewage system possibly leading to the contamination of service and drinking water. The second mortality peak at the end of the monsoon season is likely to be ascribed to hydrological reasons. The permanent heavy rainfalls during the monsoon season leading to large scale flooding are usually associated with stagnant water and the breakdown of water systems (Hashizume et al. 2007; Zhang et al. 2007a). Contamination and the spread of pathogens are possibly increasing the incidence of infectious disease and related fatalities. Moreover, the drop in temperature at the beginning of the cold season might broaden the post-monsoonal peak. A decrease in temperature has been shown to invoke negative responses of the immune system, such as reduced phagocyte activity, increased inflammatory cells or bronchoconstriction, thus leading to increased disease incidence with a particular increase in respiratory diseases (Bull 1980; Berk et al. 1987; The Eurowinter Group 1997; Keatinge et al. 2000; The Eurowinter Group 2000).

In adults and the elderly, non-communicable diseases become more dominant and in particular, cardio-respiratory diseases develop into major causes of death. The course and progress of these diseases is strongly influenced by biochemical reactions triggered by thermal conditions. Several studies have revealed adverse effects provoked by both low and high temperatures. Increased plasma and blood viscosity, elevated red blood cell counts, and increased levels of several proteins were associated with exposure to low and high temperatures (Kilbourne et al. 1982; Keatinge et al. 1984; Keatinge et al. 1986; Keatinge et al. 1989; Schneider et al. 2008). Furthermore, vasoconstriction due to cold or vasodilation due to elevated temperature can lead to a strain on the cardiovascular system that might contribute to its failure (Keatinge et al. 1984; Keatinge et al. 1986; Neild et al. 1994). Negative effects of low temperature on the immune response -as outlined above- are additionally contributing to cold-related excess mortality. Generally, it seems as if the adverse effects of cold outweigh the adverse effects of elevated temperatures leading to maximum mortality levels during the cold winter season in adults and the elderly. The intense effects of low temperatures are further expressed by the increase in mortality with decreasing (equivalent) temperature over approximately 90% of the range of values. Above a specific (equivalent) temperature, the adverse effects of heat started to emerge. However, these heat effects were not dominant enough to cause a long-lasting seasonal peak during the hot summer season. Still, short-term effects of high temperatures on mortality were observed for adults and the elderly. These effects were most pronounced after two days of exposure and then subsided slowly over the coming weeks. After a lag period of 14 days, only very minor effects were observed. Adverse effects of heat were mostly pronounced in elderly population groups of urban areas. In comparison, heat-related mortality increase in urban areas amounted to four times that of the mortality increase observed in rural areas. Moreover, when examining seasonal mortality variations on the elderly in urban areas, a summer peak emerged. This pronounced summer and heat-related excess mortality in urban areas is possibly caused by urban excess temperatures (urban heat island) as well as an increased susceptibility of urban populations to heat. On the one hand, a lack of physical activity and unhealthy dietary habits has led to a high burden of cardiovascular and other non-communicable disease, thus increasing the response to atmospheric effects. On the other hand, in urban areas a large share of the population, mostly the urban poor, are perusing high risk income generating occupations (Centre for Urban Studies 2006) demanding a great deal of physical effort (e.g., rickshaw puller, construction worker) thus making them more vulnerable to heat.

Although this study included an extensive set of mortality data quite exceptional for a developing country, the obvious limitation is rooted in the sample nature of the data set. The limited number of observations made it impossible to account for regional differences or gender or to conduct a cause-specific analysis. As no long-term air pollution data were available for Bangladesh, we could not incorporate such information into the regression modelling. To some extent, seasonal variations in air pollution were accounted for by a dummy variable. Finally, we note that the nature of this eco-epidemiological study entails the danger of the so-called ecological fallacy. Due to the aggregation of data that defines ecological studies, inferences on individual members or a subgroup need to be made carefully, as individuals or subgroups do not necessarily reflect the characteristics of a wider group (Wakefield and Salway 2001).

7.5 CONCLUSIONS

The knowledge gained from this study is of high public health interest and can help to prevent adverse atmospheric effects on health and mortality. In general, the study demonstrated that atmospheric effects on mortality are strongly age-dependent and #indicated that age-specific modifications need to be considered in any kind of public health intervention. Principally, two different atmosphere-mortality regimes with differences between fatalities occurring in groups below and above the age of 15 years were revealed. While atmospheric effects were rather weak in children and youths, adults and the elderly were subject to adverse cold and heat effects. In particular, the elderly above the age of 65 years were subject to a strong heat-related excess mortality with even stronger heat effects for those living in urban areas. Although a rise in temperatures caused by climate change might mitigate adverse cold effects, heat effects are likely to be magnified as average and extreme temperatures increase. Moreover, the projected ageing of populations in many developing countries (United Nations 2004) in combination with the increase of people living in urban areas (United Nations 2008) is likely to enhance adverse consequences of elevated temperatures. Rather unclear, so far, is the role of cold extremes. Although a decrease in the number of cold nights and days has been observed, the increase in the variance of meteorological conditions might also lead to an increase in cold extremes (Folland et al. 2001; Solomon et al. 2007). Such cold waves might well cause tremendous excess mortality.

CHAPTER 8: SYNTHESIS

8.1 SUMMARY AND MAIN FINDINGS

The first and overarching goal of this thesis was to advance the understanding of the atmosphere-mortality relationship in Bangladesh, a tropical developing country. Moreover, the modifications of this relationship by environmental framework conditions and non-atmospheric influences were investigated with special consideration of urban versus rural settings. The study also discussed future bioclimatological and meteorological impacts with regard to climate change and other ongoing processes and dynamics. A number of specific research questions were addressed which constitute the subject matter of Chapters 2-6. While the research objectives of each individual chapter were explicit in nature, this synthesis takes a more integrative approach to elaborate upon general research questions. The introduction to this thesis (Chapter 1) formulated three general research objectives.

<u>Research objective 1:</u> *To investigate short- to long-term atmospheric effects on morbidity and mortality in Bangladesh*

The findings of this thesis show a quite strong association between atmospheric conditions and health outcomes, demonstrating the existence of both seasonal effects (mid- to long-term) and more immediate meteorological impacts (short- to mid-term). In general, mortality (and morbidity[13]) were seen to peak during the cold and dry winter season. To some extent, a rudimentary summer peak during the hot and humid pre-monsoon and the beginning of the rainy season was found. Such patterns were observed for all causes as well as the most frequent causes of death, respiratory

[13] A limited amount of morbidity data (hospital data) was analysed within the scope of this thesis. The general observations made for morbidity events conform to those made for mortality data. Given the data limitations of the morbidity data, this synthesis focuses primarily on research outcomes based on mortality data.

and cardiovascular diseases. On the contrary, the data for deaths from diarrhoeal disease revealed a more complex seasonal pattern with multiple peaks associated with the rainy and the cold seasons. As diarrhoeal deaths did not account for more than 4% of all death events in Bangladesh, their relationship to atmospheric conditions shall not be discussed at this point. As for season and mortality, a strong relationship was likewise observed between temperature and mortality. Generally, an increase in all-cause and cardiovascular mortality with decreasing temperatures, i.e. a cold effect, was observed over a wide range of values. Nevertheless, an increase in mortality with increasing temperature, i.e. a heat effect, emerged above a specific threshold temperature. This threshold temperature was placed at the upper end of the temperature range, approximately at the 90th percentile. The intensity of this heat effect varied over different strata and particularly between urban and rural areas and between different age groups. In some cases, the increase in mortality above the threshold temperature outweighed the increase in mortality below the threshold, suggesting that heat effects are more severe than cold effects.

The Köppen-Geiger system[14] classifies Bangladesh as a tropical climate of the type ‘A’ (Kottek et al. 2006). Like all tropical regions, it is associated with elevated temperatures and high humidity. As shown in Chapter 3, the interplay of temperature and other meteorological parameters, particularly humidity, results in notably high equivalent temperatures (thermo-physiological indices) during the summer and monsoon seasons at a time when temperatures are already high. In Bangladesh, weather conditions during the monsoon season are typically tropical with a diurnal climate. This changes during winter, when the characteristics of a seasonal climate become apparent. Cold air masses from the Asian continent cause an abrupt fall in

[14]A detailed description of the Köppen-Geiger climate classification is given in Chapter 2. Briefly, type ‘A’ climates constitute typical tropical/equatorial climates with high temperatures and high amounts of precipitation throughout the years or at least one pronounced rainy season; type ‘B’ climates are arid/desert climates with high temperatures but low levels of precipitation; type ‘C’ climates are temperate warm climates with temperatures below those of tropical type ‘A’ climates.

temperatures during the Northeast monsoon. Nevertheless, monthly average temperatures remain above 18°C and the cold season should be considered more as a period of relative than absolute cold.

In view of the moderate temperatures observed in winter and the rather extreme temperatures measured in the summer and monsoon seasons, the dominance of winter and cold-related mortality was rather unexpected. The temperate winter conditions and the high thermal load during summer and the monsoon season would suggest a different mortality pattern. Indeed, tropical climates have been, and still are associated with excess summer mortality. The majority of studies compiled in the systematic review (Chapter 2) showed a mortality peak during the warm and rainy season. Yet in Bangladesh, a peak was observed during the winter season. Cold excess mortality has been reported before, in a study analysing data collected in the 1970s and 1980s within a vital registration system in Matlab/Bangladesh (Becker 1981; Becker and Sadar 1981; Becker and Weng 1998). The area of Matlab has been designated as an International Centre for Diarrhoeal Research, Bangladesh (ICDDR,B) study and intervention area. Ascribing their findings to the health interventions performed in this area, the authors hypothesised that other regions in Bangladesh or India would not exhibit the same pattern. The systematic review identified three more study areas, located in Brazil, Mexico and Kenya, which exhibited winter excess mortality. These regions are predominantly located in high altitudes and thus constitute temperate type ‘C’ climates with generally lower temperatures and particularly lower temperatures and during the cold season. These comparably low (winter) temperature might enforce a cold-related excess mortality. Moreover, in Brazil and Mexico, the general socio-economic status is rather high, with the burden of disease being dominated by non-communicable diseases. To date, the only equatorial type ‘A’ climate for which winter and cold-related excess mortality has been demonstrated is Bangladesh.

As argued extensively in Chapters 2, 5 and 6, excess mortality in Bangladesh during the cold season is most likely due to the decreasing prevalence of infectious and especially diarrhoeal disease. Cardio-respiratory and other non-communicable diseases have advanced to become the leading causes of death in Bangladesh. While agents provoking infectious diseases generally thrive in hot and humid conditions, the incidence of cardio-respiratory and non-communicable diseases seems to be affected by fluctuations in temperature. Temperature-induced immune responses and changes in the blood composition at low and high values seem to relate to relatively high or low temperature rather than absolute values. These conclusions accord with the findings from studies conducted in Kuwait, a type ‘B’ desert climate (Douglas et al. 1991) and moreover, reflect observations made for temperate type ‘C’ climates (e.g., Brazil, Mexico, Kenya). In this context, adaptation aspects merit further consideration. Adaptation refers to both the physiological and socio-cultural aspects of individual and populations (e.g., housing, lifestyle, and clothing). As the Bangladeshi population is exposed to high temperatures throughout most of the year, it seems to have developed a high level of adaptation to elevated thermal levels. Moreover, the wide-spread perception of the cold season as being agreeable moves many to ignore the (to them seemingly unapparent) necessity of protecting themselves against the cold. Nevertheless, relative cold appears to have adverse consequences for more susceptible individuals. Although increased levels of air pollution are likely to contribute to winter excess mortality, the high mortality levels observed during the cold season in rural areas as well as the pronounced short-term cold effects, demonstrated by regression modelling (adjusted for confounding effects), suggest the relevance of low temperatures.

<u>Research objective 2:</u> *To assess modifications of the atmosphere-mortality relationship originating from environmental framework conditions, population-specific characteristics or other non-atmospheric influences with special consideration of urban versus rural differences*

In order to assess the modifying influence of environmental framework conditions and population-specific characteristics, this study included an investigation of the atmosphere-health relationship in different strata. While both gender-specific differences and differences by socio-economic status[15] were only minor, some elementary differences were found by age and for urban versus rural areas. Whereas children and youths show a rather weak association between atmospheric conditions and mortality, winter and cold-related mortality became quite apparent for adults and the elderly. Moreover, both age groups exhibited pronounced heat effects with a notably sharp and intense increase in mortality observed for the elderly above 65 years. Summer and heat-related mortality was furthermore quite marked in urban areas. Whereas the primary winter maximum was equally strong in both areas, the urban secondary summer maximum exceeded the summer peak observed in rural areas. This urban summer excess mortality was particularly found for cardiovascular diseases. Similar observations were made for the association between mortality and temperature. In urban and rural areas comparably strong cold effects were observed, but in urban areas heat effects were stronger in terms of the observed mortality increase and the lag period over which they existed. Differences in the temperature-mortality relationship between urban and rural areas become particularly evident when considering death from cardiovascular diseases. While in rural areas no heat effect was observed at any temperature, urban areas showed a sharp increase in cardiovascular mortality above a threshold value.

[15] Socio-economic differences between different administrative units were considered (ecological level)

The macroclimatic effect exercised on the rural and urban populations led to different health outcomes, most likely due to the fact that urban and rural areas constitute two widely different physical and social environments. Basically, two aspects are very likely to be relevant in reaching any explanation of the observed differences in the atmosphere-mortality relationship between urban and rural settings. Firstly, urban areas are known to display a modified mesoclimate, the so-called urban heat island. The urban structure produces changes in the urban energy balance which result in generally higher temperatures. Chapter 3 demonstrates the existence of urban excess temperatures in Dhaka ranging around several Kelvin. Although diminished during the monsoon season, excess temperatures were pronounced during the winter and pre-monsoon seasons. While the urban heat island phenomenon could serve to mitigate cold stress during the cold season, urban excess temperatures increase the thermal load during the hot and humid (pre-monsoon) season, when temperatures are already high. In addition to such differences in the physical environment, socio-cultural aspects and a modified disease profile are potentially relevant in increasing levels of heat-related mortality in urban areas. Generally, disease patterns vary between urban and rural areas. A combination of the lack of physical activity and unhealthy nutritional habits have led to a higher prevalence of cardiovascular and other non-communicable diseases in the urban areas of developing countries (Proctor et al. 1996; Shetty 2002; Kelishadi et al. 2008; Khan et al. 2009). This high prevalence of non-communicable diseases could explain why urban populations are more susceptible to heat and hence provide an explanation for the increase in adverse heat effects registered for these areas. Moreover, for a large share of the population, mostly the urban poor that have migrated to the city, income generating activities are demanding a great deal of physical effort (e.g., rickshaw puller, construction worker) (Centre for Urban Studies 2006), presumably making them more vulnerable to heat. Most likely the higher occurrence of summer and heat-related excess mortality in urban areas stems from the combination of excess temperatures and a higher susceptibility or vulnerability of the urban population to heat effects.

<u>Research objective (3):</u> *To discuss findings against the background of global dynamics and trends such as climate change, demographic changes, urbanisation and the associated changes in the physical and social environment*

The general anticipation surrounding the likely consequences of climate change has led to a renewed scientific and political interest in the influences of atmospheric conditions on human health. This thesis has primarily demonstrated the importance of cold effects. A general rise in temperatures may well serve to mitigate these adverse cold effects. Nevertheless, this study also identified summer and heat-related excess mortality for a number of strata and causes of death. In particular, the urban areas studied were shown to be facing heat-related mortality, whether due to increased urban temperatures (the urban heat island) or an alleged greater susceptibility to heat effects. Urban cardiovascular mortality was particularly affected by summer excess mortality and heat effects. Moreover, elderly population groups were shown to face a severe heat-related increase in mortality.

An estimation of the future effects of climate and weather requires consideration of the degree and nature of the changes to which the physical, social and demographic settings are subject. Given the unabated trend towards urbanisation displayed in Bangladesh, the needs of urban populations are becoming an increasingly significant factor in the development of public health policies. In addition, the incidence of cardiovascular and other non-communicable diseases has increased in developing countries, and projections suggest that this will continue (Murray and Lopez 1997; Mathers and Loncar 2006). Moreover, in many developing countries, the number of persons aged 65 years and older is expected to increase dramatically within the next centuries (Cohen 2003; Smith and Mensah 2003; United Nations 2004). The densification of urban structures and a climate change-induced rise in temperatures makes it increasingly likely that future populations will be exposed to higher temperatures. Although increasing temperatures might mitigate cold-related mortality, the observed increase in heat-related mortality exceeded cold-related mortality. With cold effects ranging between 1% and 3%, heat effects amounted up to 20%. Considering the accumulation of the drivers outlined above – such as urbanisation, the growing prevalence of non-communicable diseases, ageing populations and rising temperatures – adverse heat effects are likely to have an ever-increasing impact. Nonetheless, several scientists have emphasised that the growing variability of meteorological conditions triggered by climate change, might not only lead to increased number of heat events, but also to an increase in absolute cold extremes, i.e. cold waves – although the number of cold day and nights has been observed to decrease (Folland et al. 2001; Solomon et al. 2007). Such cold waves might well lead to tremendous excess mortality. However, the scientific basis about the future role of cold extremes is quite limited.

8.2 STRENGTHS AND LIMITATIONS

Few studies have explored the effects of atmospheric conditions on mortality in tropical countries and this thesis represents a substantial contribution to a much-improved understanding of the relationship between atmospheric conditions and mortality in these regions. The analysis is based on continuous data from a sample registration system covering Bangladesh on a nationwide level. Such a level of data availability is quite exceptional in the context of a developing country. Civil registration systems in developing countries are often associated with incompleteness, underreporting and the absence of validation and correction of known bias (Huy et al. 2003; Mahapatra et al. 2007). The Bangladesh Sample Vital Registration System (SVRS) overcomes many of these limitations by surveying sample households and through the use of a dual recording system. Nevertheless, the data used in this study represents only a sample and is not a complete inventory. The limited number of observations precluded a detailed stratification. For instance, it was not possible to consider population-, age- and cause-specific effects in a combined analysis. Likewise, the limited nature of data availability made it impossible to account for regional or location-specific climatological and meteorological variations. While in industrialized countries, more and more research into this question is focusing on small-scale and intra-categorical differences (e.g., Medina-Ramón et al. 2006; Kaiser et al. 2007; Gabriel and Endlicher 2011), such detailed analysis could not be conducted based on the SVRS data.

Nevertheless, a certain degree of stratification was possible; this thesis revealed that atmospheric effects varied between different environments. In particular, the consideration of urban versus rural areas revealed considerable and pronounced differences in terms of seasonal variations and temperature response, while differences by gender or socio-economic status were shown to be only minor. The systematic review has highlighted the absence of research on urban-rural differences in atmospheric effects in tropical regions. Demonstrating how atmospheric effects vary between these two environments certainly represents a central achievement of this research. Moreover, this study is one of only a small number conducting a complex multivariate regression analysis of data collected in a tropical developing country. Most importantly however, this thesis has not only considered the effect of temperature on mortality, but also the combined effect of temperature and other meteorological parameters using thermo-physiological indices.

Nevertheless, some further limitations remain. In the absence of long-term air pollution data, it was not possible to consider air pollution levels in the analysis. To a certain extent, the variations could be accounted for by seasonal adjustment in the regression analysis. While a quite high reliability is attributed to the all-cause mortality data, the classification of deaths is likely to be subject to error. Causes of death were not medically certified and the somewhat rough classification is not based on ICD (International Classification of Disease) criteria. Another limitation is related to the lack of information about the socio-economic composition of the sample. Bangladeshi society consists of a wide range of different groups with different socio-economic and educational backgrounds. The nature of this eco-epidemiological study entails the danger of the so-called ecological fallacy. The aggregation of data which defines ecological studies results in a loss of information. Generally, the ecological inferences fallacy implies that individual members of a group do not necessarily display the average characteristics of a wider group (Wakefield and Salway 2001). Therefore, inferences made from a wider group to an individual level need to be made with a great deal of care. The ecological fallacy in this study might particularly arise if population groups with a quite different burden of disease and cause of death profile are aggregated.

8.3 FUTURE RESEARCH

In reaching a number of new and relevant findings, this thesis has laid the ground for future research, the nature of which lies well beyond the scope of the question in hand. This section addresses some of the paths which future research could take and subjects them to a brief discussion.

This thesis investigated the general association between temperature and mortality without consideration of extreme events such as heat or cold waves. Reference to specific examples, such as the Chicago heat wave of 1995 or the European heat wave of 2003 demonstrated that these events are associated with tremendous excess mortality (Schär and Jendritzky 2004; Kaiser et al. 2007; Robine et al. 2007). As the effect of extreme events is restricted to a rather short time frame, the research on their impact usually requires a large set of data in order to accumulate a sufficient number of cases. Due to such data requirements, the sample character of the data used in this thesis made it impossible to cover such extreme events. Nevertheless, the case-crossover approach adopted by some recent studies (e.g., Barnett 2007; Basu et al. 2008; Bell et al. 2008; Zanobetti and Schwartz 2008) could indicate a method of overcoming the data limitations constituted by a sample data. A case-crossover study defines two or more time periods for each case displaying the outcome under investigation (e.g., death): an exposure/hazard period and one or more control periods. The case-crossover design allows each person in the study to act as his or her own control which permits cases to be aggregated over several regions and time frames thus providing a greater number of cases for consideration. Despite the advantages of such an approach, it does not investigate the excess mortality registered during a particular extreme event, but restricts its focus to mortality occurring above an extreme temperature threshold (e.g., the 99th percentile).

Another worthwhile research objective could be the assessment of air pollution effects, or the combined effects of thermal conditions and air pollution respectively. Several studies have succeeded in demonstrating that varying levels of air pollution have resulted in varying levels of mortality (Pope et al. 1991; Dockery et al. 1993). In the absence of long-term data, air pollution effects could only be accounted for by the inclusion of a dummy variable in regression models. Usually, the difficulty and high maintenance costs associated with ground measurements have resulted in the move to assess air pollution by remote sensing. Aerosol optical thickness (AOT) is an aerosol optical property which correlates well with particulate matter (Kumar et al. 2007; Schaap et al. 2009). Although the spatial resolution of AOT is rather coarse, the high temporal resolution and long-term coverage of this data makes it well suited to time series analysis and assessing the short-term effects of air pollution. Daily spatial averages of AOT may serve as air pollution proxies to be incorporated into models.

This thesis also evaluated the applicability of thermo-physiological indices (TPIs) in assessing or predicting mortality. Although, the physical mechanisms triggered by humidity, air movement and radiation and their influence on the human heat balance are indisputable, TPIs were shown to have provided little predictive advantage in this analysis. The further investigation of TPIs may well represent one possible area of future research. So far, current thermo-physiological models do not make any consideration of biochemical processes. Moreover, indices are usually determined for a standardised individual of middle age and average height and weight. However, those in danger of dying from heat or cold are most likely to be of an older or younger age or to suffer from a serious and long-term medical condition (e.g., obesity, hypertonia, diabetes). Extending thermo-physiological models in this regard seems a valuable research task with considerable potential for improving their applicability in mortality prediction and thus their suitability for use in early warning systems.

8.4 CONCLUSIONS

This thesis revealed the significance of short- to long-term health effects of atmospheric thermal conditions in Bangladesh. Despite the tropical climate of the area and the associated high temperatures, the study observed a significant and high winter and cold-related excess mortality. Notwithstanding the relevance of cold-related health effects, this study revealed a secondary summer maximum and an adverse heat effect in several strata and for some causes of death. In particular, urban areas and the elderly were found to be facing a more intense and longer-lasting increase in heat-related mortality. This heat-related excess mortality was mostly pronounced for cardiovascular mortality Given the strong urbanisation trends prevalent in the areas of study, the ageing of populations and the rise in cardiovascular diseases, the incidence of adverse heat effects is likely to increase in developing countries in general and in Bangladesh in particular. Moreover, the rise in temperatures conditioned by global warming is likely to aggravate such heat effects. Preventing or mitigating excess mortality due to climate change numbers amongst the most pressing current political and public health challenges.

APPENDIX 1

SUPPLEMENTARY MATERIAL PROVIDED WITH THE MANUSCRIPT "BURKART K, KHAN MH, KRÄMER A, BREITNER S, SCHNEIDER A, ENDLICHER W (2011): SEASONAL VARIATIONS OF ALL-CAUSE AND CAUSE-SPECIFIC MORTALITY BY AGE, GENDER, AND SOCIO-ECONOMIC CONDITION IN URBAN AND RURAL AREAS OF BANGLADESH. INTERNATIONAL JOURNAL FOR EQUITY IN HEALTH, 2011, 10:32 DOI:10.1186/1475-9276-10-32." (CHAPTER 5)

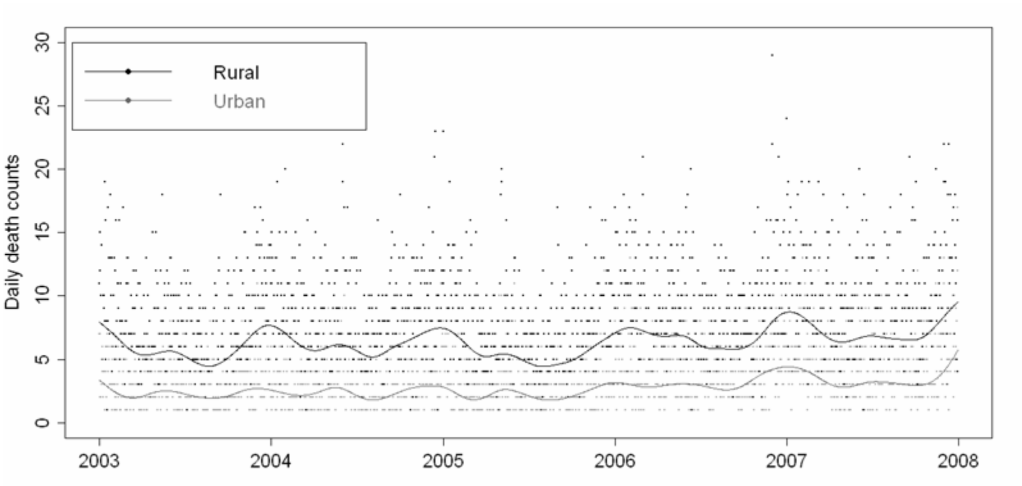

Figure A1.1a: Daily death counts in rural (black) and urban (gray) areas from 2003 to 2007 smoothed with penalized splines

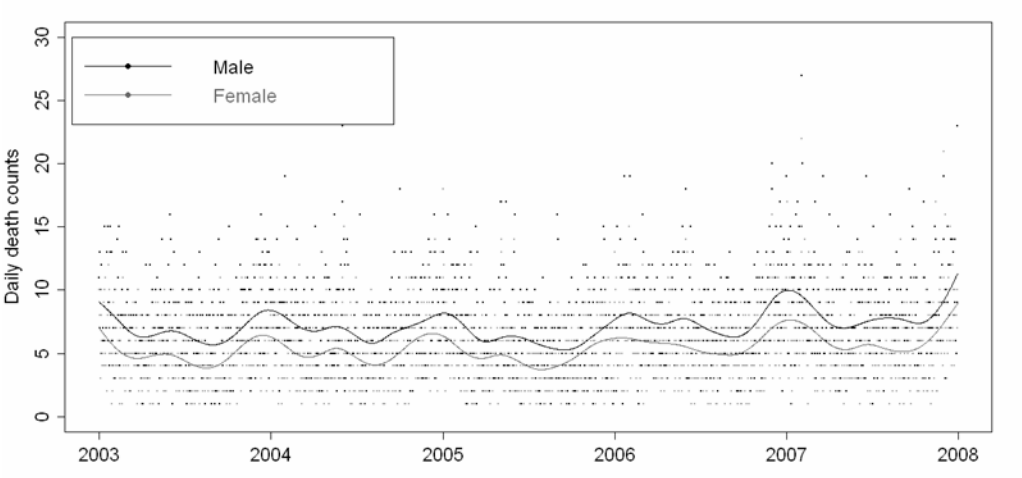

Figure 1: A1.1b: Daily death counts for males (black) and females (gray) from 2003 to 2007 smoothed with penalized splines

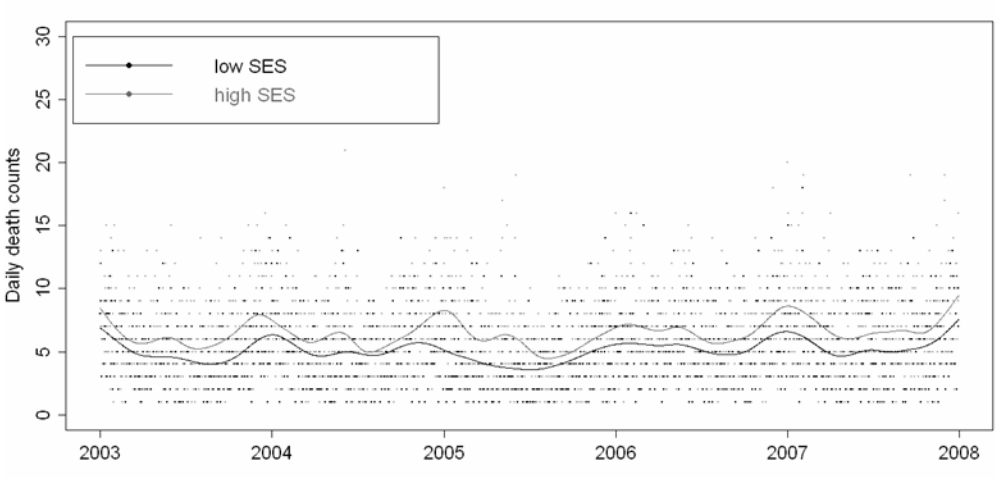

Figure A1.1c: Daily death counts for low SES (black) and high SES (gray) from 2003 to 2007 smoothed with penalized splines

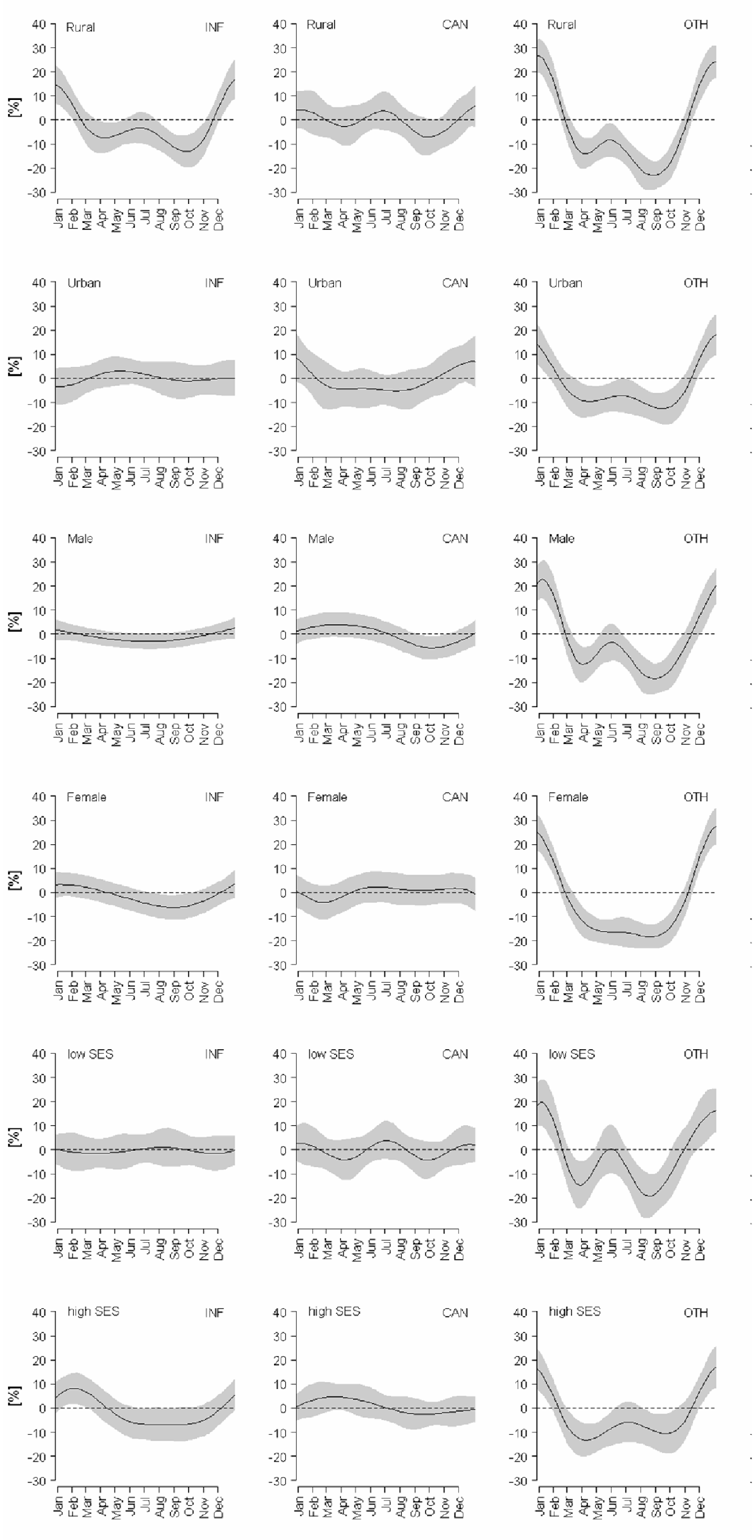

Figure A1.2: Annual seasonal mortality variations of infectious disease mortality (INF), cancer mortality (CAN), and other disease mortality (OTH) distinguished between different subcategories (rural vs. urban, male vs. female, low vs. high SES). The 95%-confidence intervals are displayed by the shaded areas

APPENDIX 2

SUPPLEMENTARY MATERIAL PROVIDED WITH THE MANUSCRIPT "BURKART K, BREITNER, S, SCHNEIDER A, KHAN MH, KRÄMER A, ENDLICHER W (2011): THE EFFECT OF ATMOSPHERIC THERMAL CONDITIONS AND URBAN THERMAL POLLUTION ON ALL-CAUSE AND CARDIOVASCULAR MORTALITY IN BANGLADESH. ENVIRONMENTAL POLLUTION, 159:2035-2043." (CHAPTER 6)

Supplementary Material: Description of the Sample Vital Registration System (SVRS)

The SVRS is a core activity of the Bangladesh Bureau of Statistics (BBS). It was initiated in 1981 and has been improved and extended over the years. Since September 2002 the SVRS comprises and surveys 1000 Primary Sample Units (PSU) in rural and urban areas, and in the statistical metropolitan area (SMA). A PSU is a compact cluster with approximately 250 households (cantonments, institutions like hotels, barracks, jails, etc., were excluded from the survey). A number of 640 PSUs is located in rural areas, comprising 132 646 households; 280 PSUs are located in urban areas with 57 852 households and 80 PSU with 16 024 household. The surveyed households consist of 4-5 household members (4.7 on average). The SVRS covers data on housing, household characteristics and population characteristics. Quarterly, the households are updated and changes in the number due to the formation of new or decay of old households (e.g., due to river erosion, migration) were recorded. Moreover, annual updates are collected on household information and characteristics, such as asset, income etc.

The strength of the SVRS is the collection of data under a dual recording system. Events are recorded continuously by a local registrar when they occur on a predesigned questionnaire (system-1). Each PSU is assigned one local registrar trained by the BBS. Moreover, events are registered in retrospective by officials from the Upazila division of BBS on a quarterly basis using the same questionnaire as the local registrar (system-2). Afterwards the two questionnaires obtained from system-1 and system-2 are matched by quality control personnel of the BBS. The events are classified into matched, partially-matched and non-matched and out-of scope events. Partially-matched and non-matched events were subject to further verification through field visits. Concerning mortality data, the following information are recorded: name of the deceased, date of birth and date of death, and sex of the deceased. Moreover, a cause of death is attributed, which, however, is not medically certified.

Supplementary Material: Region climate assessment

We considered parting Bangladesh into different climate units in order to account for spatial differences in prevailing meteorological and climatological condition. For this purpose, we followed two different approaches, for investigating differences in variability and proximity of (equivalent) temperature values.

Firstly, we conducted a factor analysis in order to assess the variability among daily (equivalent) temperature values. The Kaiser criterion is commonly used as a cut-off criterion for estimating the number of factors required to sufficiently reflect variance. For our data, the Kaiser criterion pointed out that one factor is sufficient to represent more than 99% of the variability.

While factor analysis groups variables based on their joint variation it does not consider the distance between observations. Therefore, in a second step, we conducted a cluster analysis in order to investigate whether different large-scale regional climate units become apparent (e.g., North-South differences with higher temperatures in one region and lower in the other region). Several small-scale clusters with a maximum of 3 to 4 stations came forward but no large-scale pattern emerged. This outcome suggested that clustering of stations is rather coincidental or a consequence of land use surrounding the station, but does not reflect a macro-scale pattern.

Consequently, we kept Bangladesh as one macro-climate unit and calculated spatial average (equivalent) temperature values for the whole country.

Formula A2.1: Age-adjusted mortality rate

$$Age-adjusted\ mortality\ rate = \sum r_i \cdot \left(\frac{n_{is}}{\sum n_{is}} \right)$$

i= Age group (0-4; 5-9; 10-14; 15-19; 20-24; 25-29; 30-34; 35-39; 40-44; 45-49; 50-54; 55-59; 60-64; 65-69; 70+ yrs.)

The WHO standard population was used for standardization. Age-adjusted mortality rates were calculated for each year from 2003 to 2007 and subsequently averaged.

Formula A2.2: GAM formula for all-cause mortality

$$\log(E(y_{ik})) = \beta_0 + f_1(z_{1ik}) + \beta_2 x_{2ik} + \beta_3 x_{3ik} + \beta_4 x_{4ik} + f_5(z_{5ik})$$

i=Day

k=Age group

1=Trend; *2*= Season; *3*=Day of the month; *4*=Age Group; *5*= (Equivalent) temperature

Formula A2.3: GAM formula for cardiovascular mortality

$$\log(E(y_{ik})) = \beta_0 + f_1(z_{1ik}) + \beta_2 x_{2ik} + \beta_3 x_{3ik} + f_4(z_{4ik})$$

i=Day

k=Age group

1=Trend; *2*= Season; *3*=Day of the month; *4*= (Equivalent) temperature

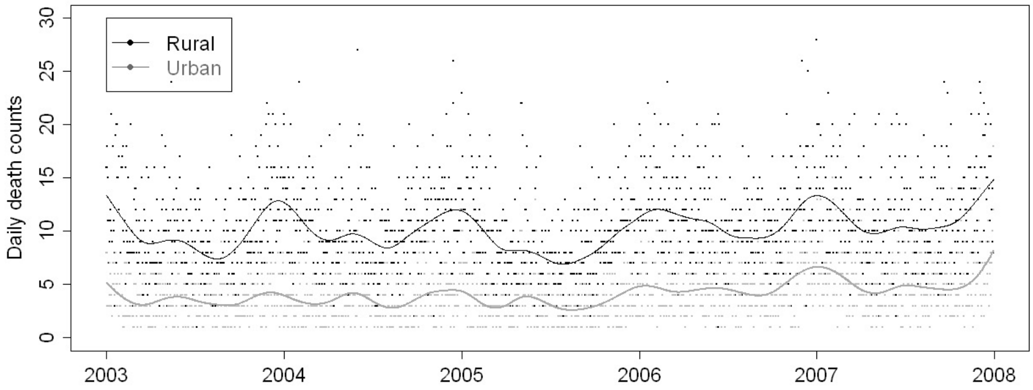

Figure A2.1: Daily death counts due to all causes in rural (black) and urban (gray) areas from 2003 to 2007 smoothed with penalized splines

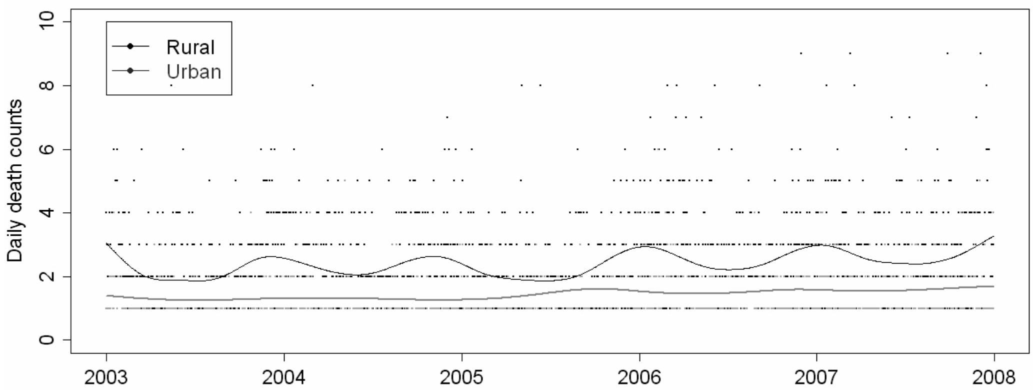

Figure A2.2: Daily death counts due to cardiovascular disease in rural (black) and urban (gray) areas from 2003 to 2007 smoothed with penalized splines

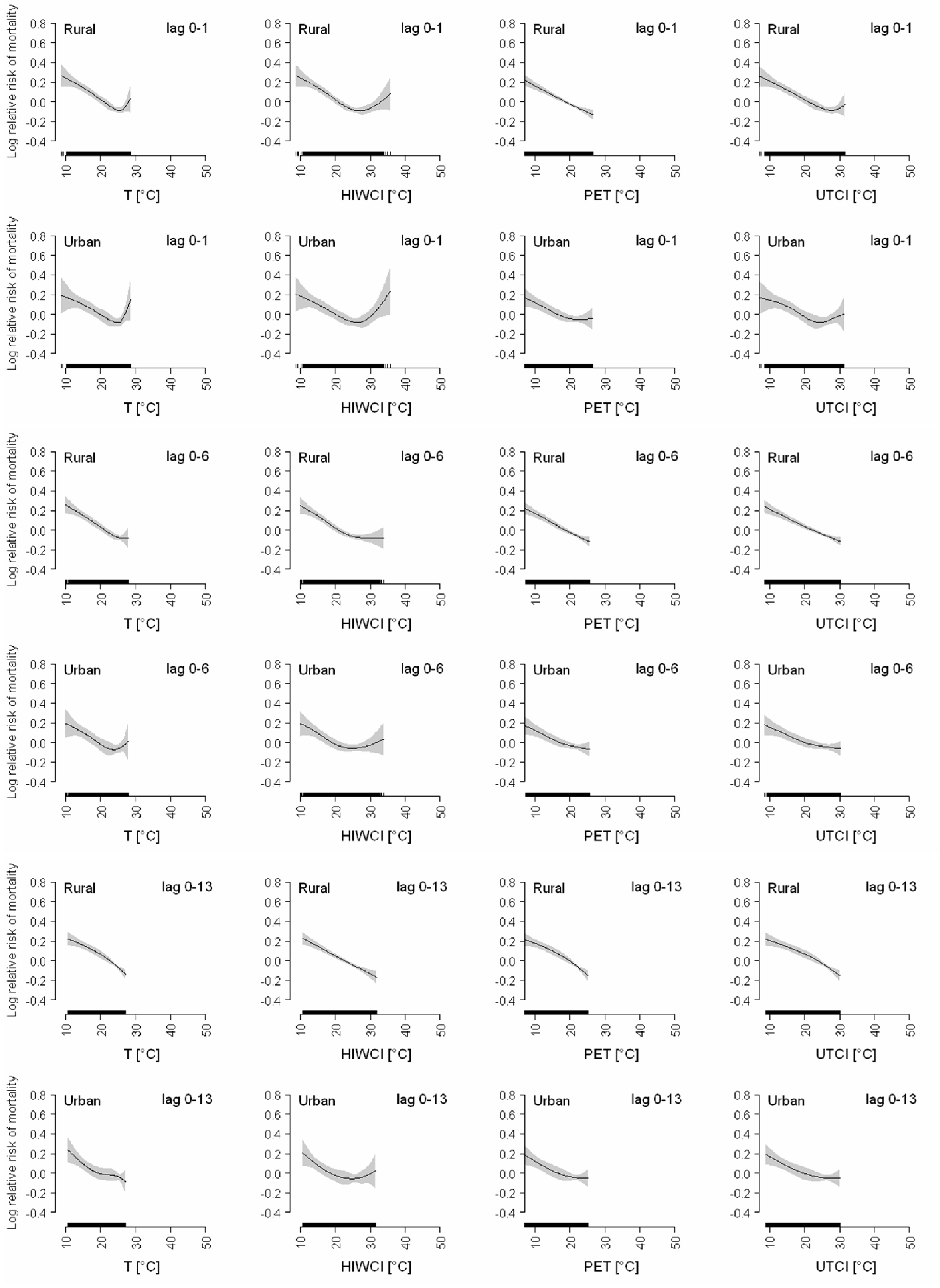

Figure A2.3: Regression curves for daily all-cause mortality on the minimum (equivalent) temperatures over the current and previous day (lag 0-1), the current and 6 previous days (lag 0-6), and the current and 13 previous days (lag 0-13). Curves are adjusted for trend, season, day of the month and age. The variable to which the plot applies (temperature or TPI) is displayed as a rug plot at the foot of each plot. The 95%-confidence intervals are displayed by the shaded area

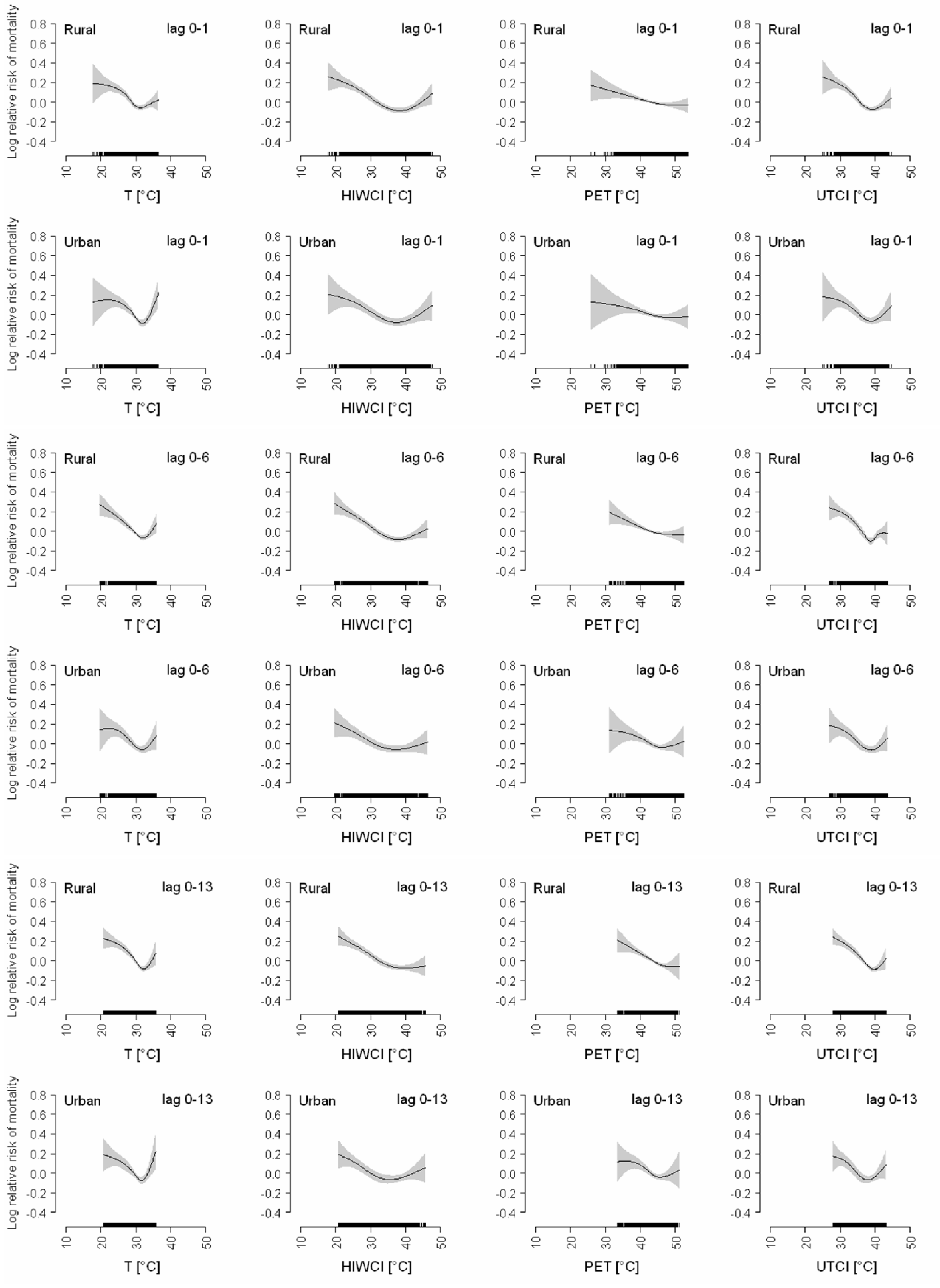

Figure A2.4: Regression curves for daily all-cause mortality on the maximum (equivalent) temperatures over the current and previous day (lag 0-1), the current and 6 previous days (lag 0-6), and the current and 13 previous days (lag 0-13). Curves are adjusted for trend, season, day of the month and age. The variable to which the plot applies (temperature or TPI) is displayed as a rug plot at the foot of each plot. The 95%-confidence intervals are displayed by the shaded area

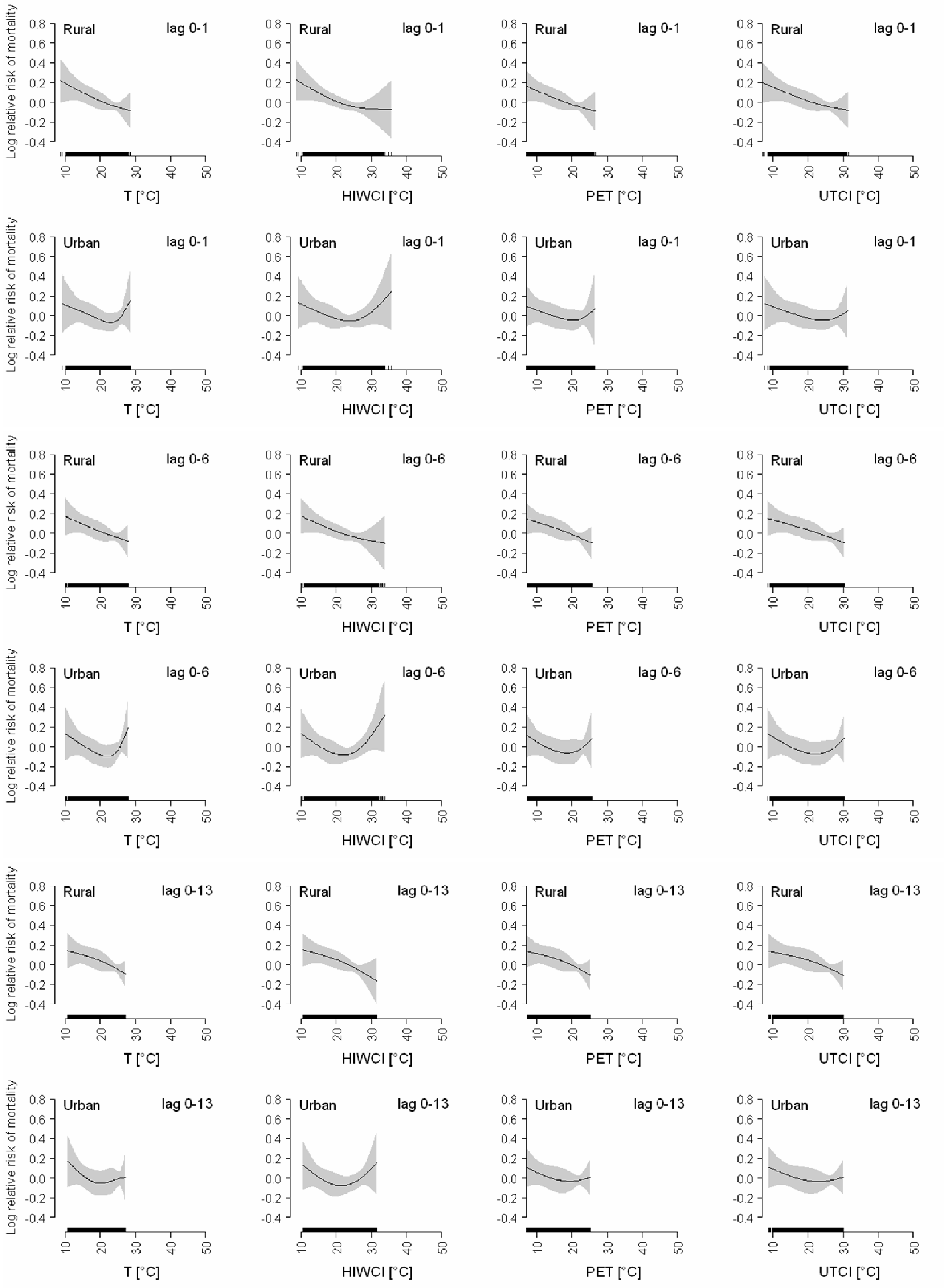

Figure A2.5: Regression curves for daily cardiovascular mortality on the minimum (equivalent) temperatures over the current and previous day (lag 0-1), the current and 6 previous days (lag 0-6), and the current and 13 previous days (lag 0-13). Curves are adjusted for trend, year, season and day of the month. The variable to which the plot applies (temperature or TPI) is displayed as a rug plot at the foot of each plot. The 95%-confidence intervals are displayed by the shaded area

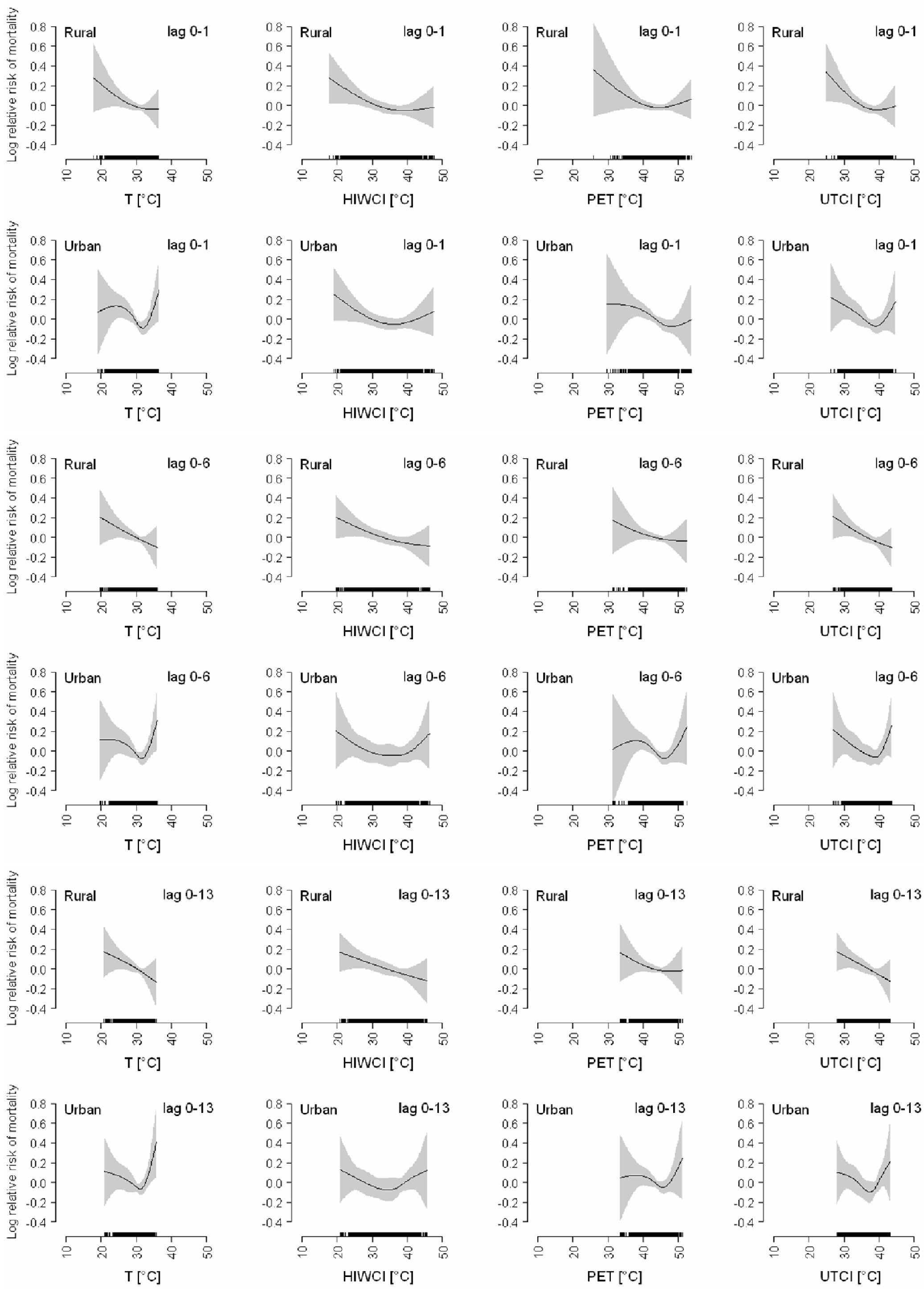

Figure A2.6: Regression curves for daily cardiovascular mortality on the maximum (equivalent) temperatures over the current and previous day (lag 0-1), the current and 6 previous days (lag 0-6), and the current and 13 previous days (lag 0-13). Curves are adjusted for trend, year, season and day of the month. The variable to which the plot applies (temperature or TPI) is displayed as a rug plot at the foot of each plot. The 95%-confidence intervals are displayed by the shaded area

Table A2.1: UBRE scores for different predictors (mean, maximum and minimum for temperature (T), Heat Index (HI), Physiological Equivalent Temperature (PET), and Universal Thermal Climate Index (UTCI))

		Rural			Urban		
		lag 0-1	lag 0-6	lag 0-13	lag 0-1	lag 0-6	lag 0-13
All-cause	**Temp.**						
	Mean	**-0,19215*)**	**-0,19108*)**	-0,18970	-0,44294	**-0,44192**)**	-0,44128
	Max	-0,18598	-0,18654	-0,18804	**-0,44360**)**	-0,44131	**-0,44172*)**
	Min	-0,19072	-0,19053	**-0,19039*)**	-0,44089	-0,43979	-0,43942
	HI						
	Mean	**-0,19223*)**	-0,19050	-0,18897	-0,44277	**-0,44144*)**	-0,44100
	Max	-0,19105	**-0,19107*)**	-0,18916	**-0,44286*)**	-0,44070	**-0,44131*)**
	Min	-0,19099	-0,19067	**-0,19046*)**	-0,44169	-0,44116	-0,43896
	PET						
	Mean	**-0,19163*)**	-0,18983	-0,18866	**-0,44127*)**	-0,43998	**-0,44033*)**
	Max	-0,17933	-0,18023	-0,18233	-0,43732	-0,43838	-0,43907
	Min	-0,19046	**-0,19126**)**	**-0,19035*)**	-0,44023	**-0,44035*)**	-0,43962
	UTCI						
	Mean	**-0,19226**)**	-0,19050	-0,18987	-0,44145	-0,44083	-0,44068
	Max	-0,19001	-0,19102	-0,19019	**-0,44191*)**	**-0,44150*)**	**-0,44241**)**
	Min	-0,19000	**-0,19120*)**	**-0,19055**)**	-0,43968	-0,44041	-0,43960
CVD	**Temp.**						
	Mean	-0,48651	**-0,48613*)**	**-0,48786**)**	-0,57778	-0,57884	-0,57690
	Max	-0,48489	-0,48513	-0,48528	**-0,58244**)**	**-0,58135**)**	**-0,58097**)**
	Min	**-0,48664*)**	-0,48594	-0,48620	-0,57663	-0,57774	-0,57600
	HI						
	Mean	**-0,48673*)**	**-0,48627**)**	-0,48641	-0,57631	-0,57715	-0,57552
	Max	-0,48627	-0,48597	-0,48599	**-0,57957*)**	-0,57530	-0,57495
	Min	-0,48659	-0,48594	**-0,48662*)**	-0,57741	**-0,57936*)**	**-0,57694*)**
	PET						
	Mean	-0,48593	-0,48576	-0,48570	-0,57580	-0,57704	-0,57538
	Max	-0,48415	-0,48374	-0,48368	**-0,58023*)**	**-0,57981*)**	-0,57686
	Min	**-0,48630*)**	**-0,48600*)**	**-0,48623*)**	-0,57542	-0,57589	**-0,57711*)**
	UTCI						
	Mean	-0,48623	-0,48618	-0,48622	-0,57568	-0,57662	-0,57476
	Max	**-0,48676**)**	**-0,48621*)**	-0,48611	**-0,57933*)**	**-0,57838*)**	**-0,57806*)**
	Min	-0,48636	-0,48606	**-0,48628*)**	-0,57551	-0,57620	-0,57702

***) best predictor comparing mean, minimum and maximum values within temperature and TPIs**
****) best predictor comparing across temperature, HIWCI, PET, and UTCI.**

Table A2.2: Thresholds and slopes of the minimum (equivalent) temperature–all-cause mortality relationship in rural and urban areas for different lag periods

	Rural			Urban		
	Threshold [°C]	Cold effects [a]	Heat effects [b]	Threshold [°C]	Cold effects [a]	Heat effects [b]
Temp. [c]						
Lag 0-1	–	2.2 (+/-0.5)	–	24.9 (+/-2.1)	2.2 (+/-0.9)	2.7 (+/-5.6)
Lag 0-6	–	2.2 (+/-0.5)	–	22.1 (+/-7.2)	2.4 (+/-1.8)	0.7 (+/-2.4)
Lag 0-13	–	2.2 (+/-0.5)	–	–	1.6 (+/-0.8)	–
HI [d]						
Lag 0-1	25.2 (+/- 2.2)	2.4 (+/-0.5)	0.3 (+/-1.4)	25.5 (+/-2.8)	2.1 (+/-0.9)	1.5 (+/-2.0)
Lag 0-6	–	1.9 (+/-0.4)	–	25.3 (+/-3.4)	2.0 (+/-0.8)	1.1 (+/-2.4)
Lag 0-13	–	2.1 (+/-0.4)	–	19.6 (+/- 6.5)	2.7 (+/-1.7)	0.7 (+/-1.0)
PET [e]						
Lag 0-1	–	2.0 (+/-0.4)	–	–	1.5 (+/-0.7)	–
Lag 0-6	–	2.0 (+/-0.4)	–	–	1.5 (+/-0.7)	–
Lag 0-13	–	2.0 (+/-0.4)	–	–	1.4 (+/-0.7)	–
UTCI [f]						
Lag 0-1	29.1 (+/-0.8)	1.8 (+/-0.4)	4.5 (+/-10.0)	26.1 (+/-4.3)	1.9 (+/-0.9)	1.4 (+/-2.7)
Lag 0-6	–	1.8 (+/-0.4)	–	–	1.3 (+/-0.6)	–
Lag 0-13	–	1.7 (+/-0.4)	–	–	1.2 (+/-0.6)	–

[a] Percentage increase in mortality for each °C decrease in (equivalent) temperature below threshold (95% CI)
[b] Percentage increase in mortality for each °C increase in (equivalent) temperature above threshold (95% CI)
[c] Temperature
[d] Heat Index/Wind Chill Index
[e] Physiological Equivalent Temperature
[f] Universal Thermal Climate Index

Table A2.3: Thresholds and slopes of the maximum (equivalent) temperature–all-cause mortality relationship in rural and urban areas for different lag periods

	Rural			Urban		
	Threshold [°C]	Cold effects [a]	Heat effects [b]	Threshold [°C]	Cold effects [a]	Heat effects [b]
Temp. [c]						
Lag 0-1	32.5 (+/-0.9)	2.8 (+/-0.8)	2.3 (+/-3.7)	32.9 (+/-0.9)	2.8 (+/-1.2)	6.1 (+/-7.0)
Lag 0-6	31.6 (+/-0.8)	3.5 (+/-0.9)	2.0 (+/-2.7)	33.7 (+/-1.0)	3.0 (+/-1.2)	15.1 (+/-14.4)
Lag 0-13	30.3 (+/-0.7)	2.9 (+/-0.8)	1.3 (+/-2.2)	30.2 (+/-1.1)	2.2 (+/-1.0)	3.5 (+/-3.2)
HI [d]						
Lag 0-1	39.1 (+/-1.4)	1.3 (+/-0.4)	1.7 (+/-1.5)	32.6 (+/-3.3)	1.0 (+/-0.6)	0.9 (+/-1.1)
Lag 0-6	37.5 (+/-1.9)	1.5 (+/-0.4)	1.2 (+/-1.3)	30.2 (+/-2.5)	1.1 (+/-0.6)	0.4 (+/-1.0)
Lag 0-13	36.6 (+/-3.8)	1.7 (+/-0.4)	0.3 (+/-1.4)	29.8 (+/-1.7)	1.0 (+/-0.6)	0.8 (+/-1.1)
PET [e]						
Lag 0-1	–	0.9 (+/-0.4)	–		0.8 (+/-0.7)	
Lag 0-6	–	1.2 (+/-0.5)	–	45.9 (+/-1.7)	2.0 (+/-1.2)	2.2 (+/-3.3)
Lag 0-13	–	1.9 (+/-0.6)	–	41.6 (+/-6.9)	2.7 (+/-1.2)	0.9 (+/-3.8)
UTCI [f]						
Lag 0-1	39.4 (+/-0.9)	3.1 (+/-0.7)	2.2 (+/-2.4)	39.9 (+/-1.1)	2.7 (+/-1.1)	4.6 (+/-4.6)
Lag 0-6	39.3 (+/-0.8)	3.4 (+/-0.8)	2.7 (+/-2.8)	39.8 (+/-1.1)	2.7 (+/-1.2)	5.5 (+/-4.8)
Lag 0-13	40.3 (+/-1.4)	3.1 (+/-0.7)	1.2 (+/-5.1)	38.7 (+/-1.6)	2.8 (+/-1.3)	5.2 (+/-4.4)

[a] Percentage increase in mortality for each °C decrease in (equivalent) temperature below threshold (95% CI)
[b] Percentage increase in mortality for each °C increase in (equivalent) temperature above threshold (95% CI)
[c] Temperature
[d] Heat Index/Wind Chill Index
[e] Physiological Equivalent Temperature
[f] Universal Thermal Climate Index

Table A2.4: Thresholds and slopes of the minimum (equivalent) temperature–cardiovascular mortality relationship in rural and urban areas for different lag periods

	Rural			Urban		
	Threshold [°C]	Cold effects [a]	Heat effects [b]	Threshold [°C]	Cold effects [a]	Heat effects [b]
Temp. [c]						
Lag 0-1	–	0.9 (+/-1.3)	–	25.7 (+/- 4.4)	0.5 (+/-1.7)	2.9 (+/-14.8)
Lag 0-6	–	0.9 (+/-1.4)	–	21.0 (+/-15.7)	1.0 (+/-3.6)	1.8 (+/-5.2)
Lag 0-13	–	0.9 (+/-1.4)	–	26.3 (+/- 4.2)	0.3 (+/-1.6)	10.4 (+/-40.6)
HI [d]						
Lag 0-1	–	0.8 (+/-1.1)	–	26.3 (+/- 8.9)	0.5 (+/-1.8)	1.2 (+/-4.0)
Lag 0-6	–	0.8 (+/-1.2)	–	24.0 (+/- 9.8)	0.9 (+/-2.2)	2.0 (+/-4.3)
Lag 0-13	–	0.8 (+/-1.3)	–	21.6 (+/-21.7)	0.9 (+/-3.4)	1.5 (+/-4.0)
PET [e]						
Lag 0-1	–	0.8 (+/-1.2)	–	20.6 (+/-22.2)	0.6 (+/-2.2)	1.3 (+/-7.0)
Lag 0-6	–	0.8 (+/-1.2)	–	19.3 (+/-23.2)	0.7 (+/-1.9)	1.4 (+/-10.6)
Lag 0-13	–	0.8 (+/-1.2)	–	17.3 (+/-42.0)	0.9 (+/-3.9)	0.6 (+/-4.2)
UTCI [f]						
Lag 0-1	–	0.7 (+/-1.1)	–	25.4 (+/-18.7)	0.6 (+/-1.7)	0.4 (+/-7.5)
Lag 0-6	–	0.7 (+/-1.1)	–	20.1 (+/-23.3)	0.8 (+/-3.1)	0.8 (+/-3.6)
Lag 0-13	–	0.7 (+/-1.1)	–	–	0.2 (+/-1.3)	–

[a] Percentage increase in mortality for each °C decrease in (equivalent) temperature below threshold (95% CI)
[b] Percentage increase in mortality for each °C increase in (equivalent) temperature above threshold (95% CI)
[c] Temperature
[d] Heat Index/Wind Chill Index
[e] Physiological Equivalent Temperature
[f] Universal Thermal Climate Index

Table A2.5: Thresholds and slopes of the maximum (equivalent) temperature–cardiovascular mortality relationship in rural and urban areas for different lag periods

	Rural			Urban		
	Threshold [°C]	Cold effects [a]	Heat effects [b]	Threshold [°C]	Cold effects [a]	Heat effects [b]
Temp. [a]						
Lag 0-1	–	1.1 (+/-1.8)	–	33.0 (+/-2.1)	1.8 (+/-2.5)	6.6 (+/-15.1)
Lag 0-6	–	1.4 (+/-2.0)	–	32.3 (+/-2.3)	1.2 (+/-2.7)	6.2 (+/-12.2)
Lag 0-13	–	1.4 (+/-2.2)	–	33.0 (+/-2.0)	0.7 (+/-2.7)	13.1 (+/-25.9)
HI [b]						
Lag 0-1	–	0.6 (+/-1.0)	–	38.6 (+/-6.4)	0.9 (+/-1.6)	1.3 (+/-4.7)
Lag 0-6	–	0.8 (+/-1.1)	–	34.3 (+/-11.2)	1.1 (+/-2.4)	0.8 (+/-3.2)
Lag 0-13	–	0.7 (+/-1.1)	–	33.7 (+/-11.6)	1.2 (+/-2.7)	1.5 (+/-3.5)
PET [c]						
Lag 0-1	47.0 (+/-3.7)	1.1 (+/-1.6)	2.6 (+/- 6.3)	46.5 (+/-5.9)	1.6 (+/-2.0)	0.9 (+/- 7.1)
Lag 0-6	–	0.7 (+/-1.5)	–	46.5 (+/-3.3)	1.3 (+/-2.4)	3.7 (+/- 8.4)
Lag 0-13	–	0.8 (+/-1.7)	–	46.7 (+/-4.5)	0.7 (+/-2.4)	3.5 (+/-18.0)
UTCI [d]						
Lag 0-1	39.0 (+/- 5.2)	1.6 (+/-1.9)	2.4 (+/-11.7)	40.2 (+/-2.2)	1.6 (+/-2.4)	5.8 (+/- 8.9)
Lag 0-6	–	1.3 (+/-1.8)	–	39.4 (+/-2.4)	1.3 (+/-2.4)	5.2 (+/-12.0)
Lag 0-13	–	1.2 (+/-1.8)	–	40.0 (+/-1.8)	0.8 (+/-2.3)	8.8 (+/-14.2)

[a] Percentage increase in mortality for each °C decrease in (equivalent) temperature below threshold (95% CI)
[b] Percentage increase in mortality for each °C increase in (equivalent) temperature above threshold (95% CI)
[c] Temperature
[d] Heat Index/Wind Chill Index
[e] Physiological Equivalent Temperature
[f] Universal Thermal Climate Index

APPENDIX 3

SUPPLEMENTARY MATERIAL PROVIDED WITH THE MANUSCRIPT "BURKART K, ENDLICHER W (2011): AGE-SPECIFIC ANALYSIS OF SHORT- AND LONG-TERM METEOROLOGICAL EFFECTS ON MORTALITY IN BANGLADESH, *IN PREPARATION*." (CHAPTER 7)

Formula A3.1: GAM formula seasonality assessment

$$\log(E(y_i)) = \beta_0 + f_1(z_{1i}) + f_2(z_{2i})$$

i=Day
1=Trend; *2*= Season; 2=Day of the month;

Formula A3.1: GAM formula for assessment of thermal effects

$$\log(E(y_i)) = \beta_0 + f_1(z_{1i}) + \beta_2 x_{2i} + \beta_3 x_{3i} + \beta_4 + f_4(z_{4i})$$

i=Day
k=Age group
1=Trend; *2*= Season; *3*=Day of the month; *4*= (Equivalent) temperature

Table A3.1: Age-specific mortality rates per 100,000 in Bangladesh in urban areas

	Infants and Children (0-4 yrs.)	Youths (5-14 yrs.)	Adults (15-64 yrs.)	Elderly (65+ yrs.)
Respiratory disease	313.2	11.3	39.3	603.1
Cardiovascular disease	12.1	4.9	106.8	1036.2
Diarrhoeal disease	62.0	4.6	5.8	73.4
Infectious disease	184.6	8.9	21.6	277.4
Cancer	14.1	2.5	1.4	10.7
Vector-borne disease	5.4	5.5	46.2	241.6
Malnutrition	68.7	1.2	1.9	16.1
Others	192.6	21.4	102.9	3198.1

Table A3.2: Age-specific mortality rates per 100,000 in Bangladesh in rural areas

	Infants and Children (0-4 yrs.)	Youths (5-14 yrs.)	Adults (15-64 yrs.)	Elderly (65+ yrs.)
Respiratory disease	441.0	13.6	45.9	874.2
Cardiovascular disease	11.5	4.4	62.7	681.4
Diarrhoeal disease	94.6	11.8	9.5	109.3
Infectious disease	295.5	25.0	29.1	432.4
Cancer	36.1	4.9	4.0	34.3
Vector-borne disease	5.3	5.6	39.4	258.4
Malnutrition	71.4	4.4	3.2	32.8
Others	292.6	34.9	114.8	3546.8

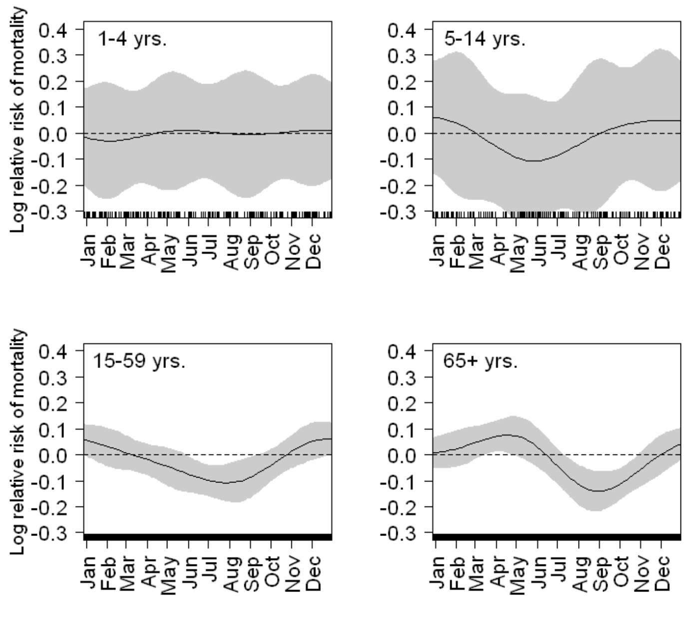

Figure A3.1: Seasonal variations of all-cause mortality in urban areas for four different age groups. The frequency of observations is indicated by the rug plot on the foot of each diagram. The 95%-confidence intervals are displayed by the shaded area

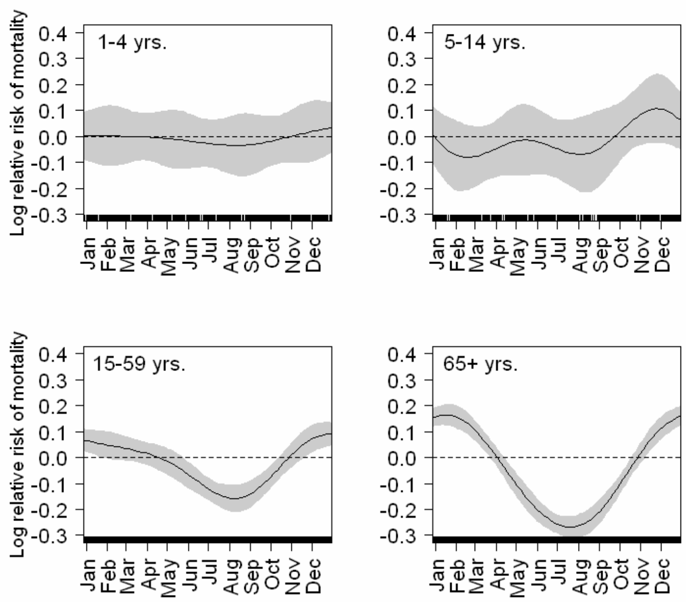

Figure A3.2: Seasonal variations of all-cause mortality in rural areas for four different age groups. The frequency of observations is indicated by the rug plot on the foot of each diagram. The 95%-confidence intervals are displayed by the shaded area

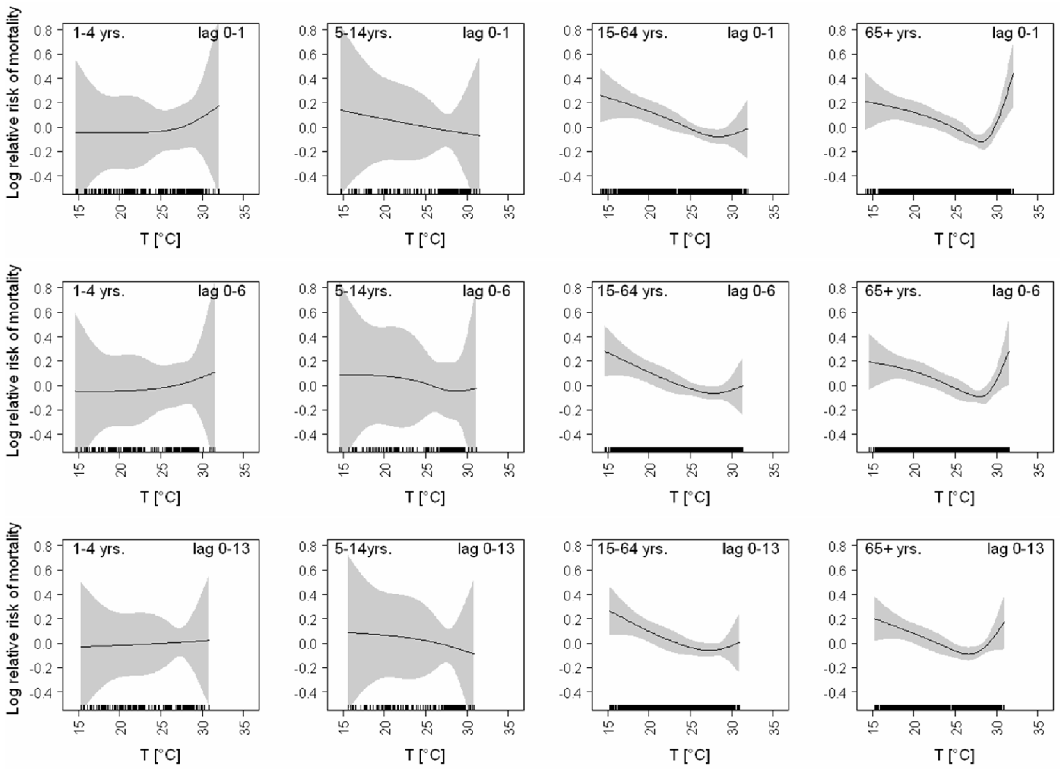

Figure A3.3: Regression curves for daily all-cause mortality on the mean temperatures over several lag periods and for different age groups in urban areas. The curves are adjusted for trend, season, and day of the month. The frequency of observations is indicated by the rug plot on the foot of each diagram. The 95%-confidence intervals are displayed by the shaded area

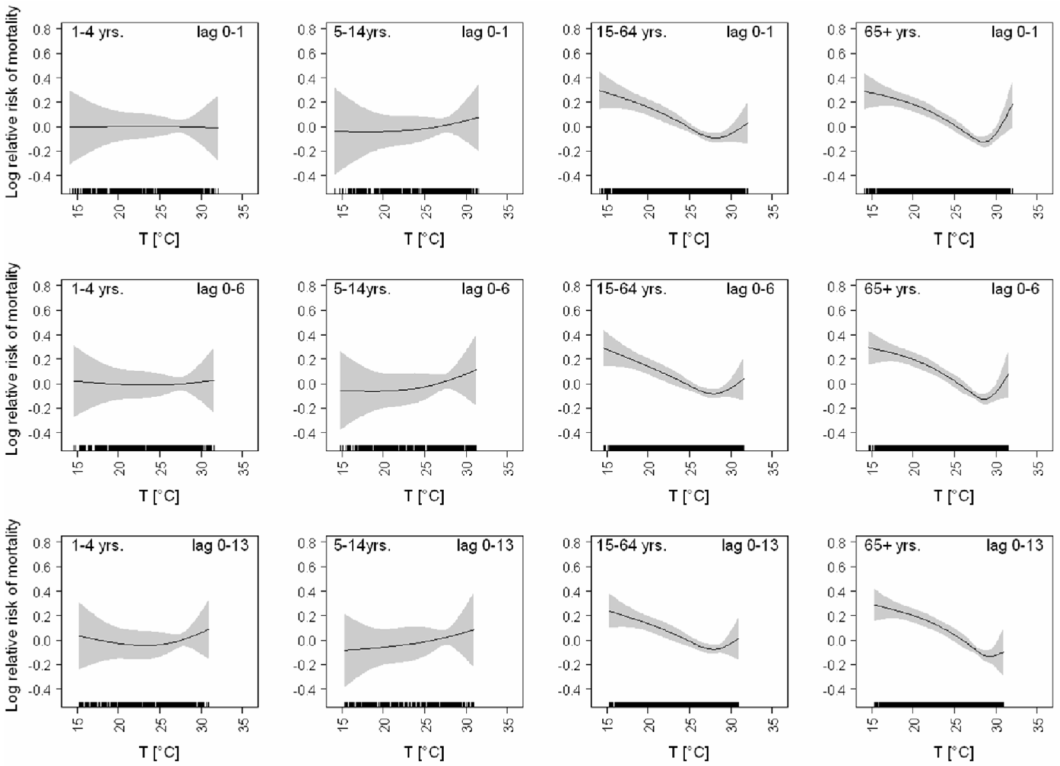

Figure A3.4: Regression curves for daily all-cause mortality on the mean temperatures over several lag periods and for different age groups in rural areas. The curves are adjusted for trend, season, and day of the month. The frequency of observations is indicated by the rug plot on the foot of each diagram. The 95%-confidence intervals are displayed by the shaded area

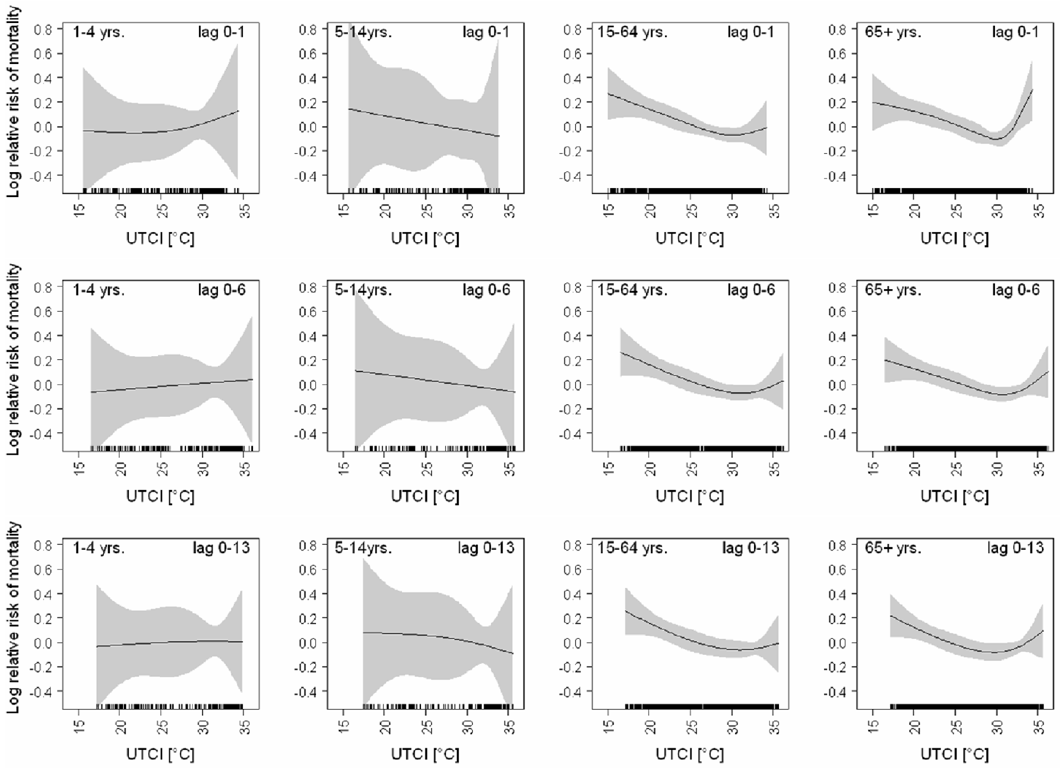

Figure A3.5: Regression curves for daily all-cause mortality on the mean UTCI over several lag periods and for different age groups in urban areas. Curves are adjusted for trend, season, and day of the month. The frequency of observations is indicated by the rug plot on the foot of each diagram. The 95%-confidence intervals are displayed by the shaded area

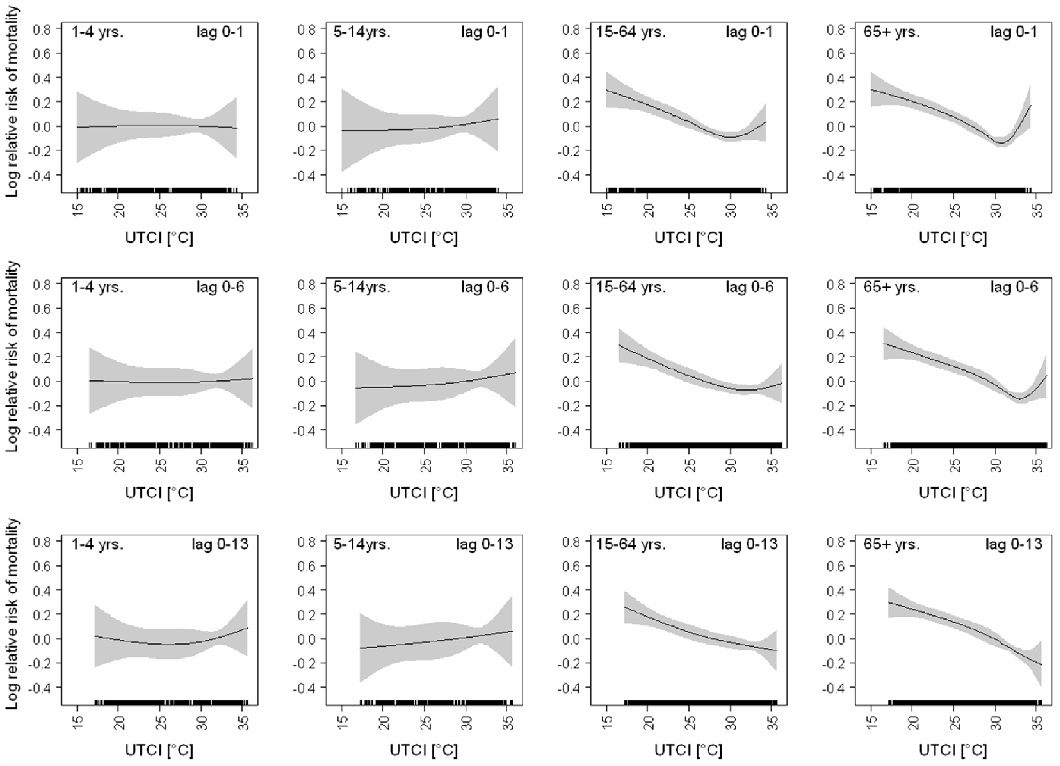

Figure A3.6: Regression curves for daily all-cause mortality on the mean UTCI over several lag periods and for different age groups in rural areas. Curves are adjusted for trend, season, and day of the month. The frequency of observations is indicated by the rug plot on the foot of each diagram. The 95%-confidence intervals are displayed by the shaded area

Table A3.3: Thresholds and slopes of the mean temperature/universal thermal climate index (UTCI)–all-cause mortality relationship for different lag periods in urban areas

	Children (1-4 yrs.)			Youths (5-14 yrs.)			Adults (15-64 yrs.)			Elderly (65+ yrs.)		
	Threshold [℃]	Cold effect [a]	Heat effect [b]	Threshold [℃]	Cold effect [a]	Heat effect [b]	Threshold [℃]	Cold effect [a]	Heat effect [b]	Threshold [℃]	Cold effect [a]	Heat effect [b]
Temp.[c]												
Lag 0-1			0.7 (+/-4.4)		1.3 (+/-5.6)		27.3 (+/-1.2)	2.7 (+/-2.0)	0.5 (+/-4.5)	29.3 (+/-0.4)	2.6 (+/-1.4)	20.1 (+/-12.7)
Lag 0-6			0.7 (+/-4.4)		1.1 (+/-5.6)		25.9 (+/-1.5)	3.3 (+/-2.0)	0.7 (+/-5.4)	29.3 (+/-0.5)	2.4 (+/-1.4)	17.9 (+/-16.9)
Lag 0-13			0.3 (+/-4.6)		1.2 (+/-5.7)		27.6 (+/-6.2)	2.6 (+/-1.7)	2.5 (+/-9.0)	28.2 (+/-5.8)	2.4 (+/-1.5)	7.9 (+/- 9.6)
UTCI [d]												
Lag 0-1			0.7 (+/-4.0)		1.3 (+/-5.0)		29.6 (+/-1.3)	2.7 (+/-1.6)	1.1 (+/-5.7)	31.7 (+/-0.4)	2.1 (+/-1.2)	19.8 (+/-13.0)
Lag 0-6			0.5 (+/-3.6)		1.0 (+/-4.6)		30.8 (+/-2.3)	2.7 (+/-1.4)	0.3 (+/-6.5)	34.5 (+/-0.5)	1.6 (+/-1.1)	18.7 (+/-27.3)
Lag 0-13			0.2 (+/-3.7)		1.0 (+/-4.5)		31.8 (+/-7.4)	2.2 (+/-1.4)	1.4 (+/-8.6)	28.2 (+/-0.0)	2.8 (+/-1.9)	3.66 (+/- 4.5)

[a] Percentage increase in mortality for each ℃ decrease in (equivalent) temperature below threshold (95% Confidence intervals)
[b] Percentage increase in mortality for each ℃ increase in (equivalent) temperature above threshold (95% Confidence intervals)
[c] Temperature
[d] Universal Thermal Climate Index

Table A3.4: Thresholds and slopes of the mean temperature/universal thermal climate index (UTCI)–all-cause mortality relationship for different lag periods in rural areas

	Children (1-4 yrs.)			Youths (5-14 yrs.)			Adults (15-64 yrs.)			Elderly (65+ yrs.)		
	Threshold [℃]	Cold effect [a]	Heat effect [b]	Threshold [℃]	Cold effect [a]	Heat effect [b]	Threshold [℃]	Cold effect [a]	Heat effect [b]	Threshold [℃]	Cold effect [a]	Heat effect [b]
Temp. [c]												
Lag 0-1			0.0 (+/-2.1)			0.6 (+/-2.5)	28.1 (+/-1.2)	3.0 (+/-1.1)	2.0 (+/-4.8)	28.4 (+/-0.4)	3.5 (+/-0.9)	4.2 (+/- 7.3)
Lag 0-6			0.1 (+/-2.2)			0.8 (+/-2.5)	26.9 (+/-1.5)	3.2 (+/-1.3)	1.0 (+/-3.9)	29.0 (+/-0.5)	3.5 (+/-0.8)	4.5 (+/-13.7)
Lag 0-13			0.3 (+/-2.2)			0.9 (+/-2.5)	26.9 (+/-6.2)	3.0 (+/-1.47)	1.0 (+/-4.2)		3.4 (+/-0.8)	
UTCI [d]												
Lag 0-1			0.0 (+/-1.9)			0.4 (+/-2.2)	30.3 (+/-1.3)	2.7 (+/-1.0)	2.0 (+/-4.8)	31.1 (+/-0.4)	3.1 (+/-0.8)	6.1 (+/-8.1)
Lag 0-6			0.1 (+/-1.8)			0.5 (+/-2.0)	31.3 (+/-2.3)	2.5 (+/-1.0)	0.7 (+/-4.4)	33.5 (+/-0.5)	2.9 (+/-0.7)	3.5 (+/-8.0)
Lag 0-13			0.3 (+/-1.8)			0.6 (+/-2.0)		1.8 (+/-0.8)			3.4 (+/-0.8)	

[a] Percentage increase in mortality for each ℃ decrease in (equivalent) temperature below threshold (95% Confidence intervals)
[b] Percentage increase in mortality for each ℃ increase in (equivalent) temperature above threshold (95% Confidence intervals)
[c] Temperature
[d] Universal Thermal Climate Index

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EIDESSTATTLICHE ERKLÄRUNG

Hiermit erkläre ich, die vorliegende Dissertation selbstständig und ohne Verwendung unerlaubter Hilfe angefertigt zu haben. Die aus fremden Quellen direkt oder indirekt übernommenen Inhalte sind als solche kenntlich gemacht. Die Dissertation wird erstmalig und nur an der Humboldt-Universität zu Berlin eingereicht. Weiterhin erkläre ich, nicht bereits einen Doktortitel im Fach Geographie zu besitzen. Die dem Verfahren zu Grunde liegende Promotionsordnung ist mir bekannt.

Katrin Burkart

Berlin, 9. März 2011